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CONTENTS

ORGANIZATIONAL PROCESSES IN SOCIAL WELFARE PROGRAMS: A CASE STUDY

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Programs of social welfare have grown dramatically in this country during the six decades of this century. From local neighborhood settlement houses and publicly supported asylums, social welfare has grown into a complex system of public and private associations which function at the national, state, and local levels, and which annually consume billions of dollars in efforts to solve the problems of individuals and of the society. The social welfare professions generally, and social work particularly, have dealt primarily with intrapsychic processes in the individuals in their efforts to solve these problems. Indeed, welfare services today are distinguished by the fact that their approach is so completely psychological and individualistic in character. And explanations for the success or failure of welfare efforts are also sought at this level. It is within the personality of the individual that the causes of his problems are sought, and the outcome of attempts to help him are said to be determined by deep-seated psychological processes. The importance of psychological factors to the success or failure of a program cannot be overlooked. Yet, the almost exclusive focus on such factors has diverted general attention away from a very important fact; namely, that social welfare programs are enshrined in large-scale organizations which are subject to the structural pressures common to all complex bureaucracies. And the success or failure of a program of welfare services is as much determined by the bureaucratic structure which houses it as it is by intrapsychic forces in the individuals who receive the services.

The purpose of this paper is to analyze one kind of social welfare association that has failed to achieve its goals in order to shed some light on the important influence that bureaucratic structure can have on the outcome of a program. The case study, which is of sheltered workshops for the blind, is an especially good one because these organizations typify in many ways social welfare programs in America. While we shall deal with only one kind of association, the point of our analysis has implications that extend across the entire range of social welfare in this country.

Data about organizations in the field of employment of the blind come from an analysis of publications in work for the blind, including the major professional journals in that field and the proceedings of professional associations of workers for the blind. Corroborative support for findings based upon these data come from two sources: *(1)* interviews with employment specialists in work for the blind, and *(2)* visits to special employment facilities for the blind.

In the field of employment of the blind three types of programs have traditionally existed: *(1)* A home industries program offers seriously disabled blind persons an opportunity to earn a modest income by assembling and finishing products brought to them by a representative of the state commission or local agency for the blind. These persons are free to work at their own pace, and their products are subsequently sold through sales rooms of agencies and commissions for the blind or at church and service club benefits. *(2)* Sheltered workshops provide gainful employment for certain kinds of blind persons. These workshops (often referred to as "broomshops") specialize in the manufacture of a few standard products selected both for the ease with which they can be assembled and for their marketing potential. In sheltered workshops blind persons are taught broom- and mop-making, rug-weaving, chair-caning, willow work, and similar crafts. Finished products are identified as "blind-made products"; they are sold to the government, big industries, or directly to the individual consumer. *(3)* Attempts are made to place blind men and women in competitive commercial industry, where they work side by side with sighted persons. The assumption is made that in every factory and industrial plant there is a number of jobs that do not require sight and that trained blind persons can perform as ably as sighted persons. Commercial employment programs have placement officers whose job is to locate such positions in industries in the community, to find interested and qualified blind persons who might fill them, and to train such persons for the positions. After employment is secured, the placement officer is expected to act as a liaison among the blind worker, his employer, and the sponsoring agency.

It was commonly agreed from the very beginning of organized work for the blind that the most desirable form of employment for blind workers was in commercial industry. This philosophy was first formally presented in 1905 at the annual meetings of the American Association of Workers for the Blind (AAWB) by Mr. Charles Campbell, head of the Massachusetts State Commission for the Blind. Mr. Campbell stated that the purpose of the Massachusetts Commission was "to enable blind persons to become selling agents, and when possible, to become wage earners in shops or factories for the seeing" (1). It was his belief that "every able-bodied blind person . . . can find work of some kind side by side with seeing people if efforts are persistently made in this direction" (2). He went on: "It is merely a question of time before blind operatives become an accepted part of the great army of factory workers" (3). These views were reiterated by Mr. Campbell and others during the early 1900s, and they have been continually expressed through the years, up through the present time, in major policy statements by influential people in the field of work for the blind (4).

It was recognized by most employment specialists, however, that the goal of employment of the blind in commercial industry was not always attainable. Some blind persons were so disabled

that they could not compete in commercial industry; others were blinded in later life and could not make a good enough adjustment to their visual loss to be considered for commercial work. For these persons sheltered workshops were seen as the most appropriate places for work. In sheltered workshops production norms were less stringent than they were in commercial industry; equipment was specially adapted to the requirements of blind operatives; piece rates were generally higher per unit of production than in commercial industry; and a minimum wage (5) was ordinarily guaranteed regardless of the workers' productivity level. The sheltered workshop was, therefore, primarily a *social service* for blind persons. This fact was emphasized by a leading employment specialist, Mr. J. N. Smith, in the 1937 *Outlook:* "While following the methods of industry to some extent, the sheltered workshops are not and never can be businesses or industries; the welfare of the client, and not profit, is the goal" (6). Sheltered workshops were expected to operate at a deficit because their economics were special and different from those of commercial factories.

Sheltered workshops had two secondary functions. They were expected to serve as laboratories for evaluating and training blind persons for placement in commercial industry; and they were expected to absorb blind men and women who were competent to work in commercial industry but who were unable to find jobs because of adverse economic conditions.

While the two employment programs were intended to go hand in hand, the organizational requirements of each differed considerably. Programs of industrial placement require a placement officer who is conversant with general economic and industrial conditions in the community. He is required to visit industrial settings continually in order to discover (and often to create) positions for blind persons. He needs to evaluate the blind person's potential for various openings and to train him for those for which he is suited. If economic conditions lead to unemployment, the placement officer is then faced with the task of locating a new position suitable for his client. This program requires a great deal of inventiveness and individual attention on the part of the placement officer. It also requires him to spend the greater part of his time in the community, acting as a liaison between the blind person and the industries of the community. Aside from a small supporting staff the burden of successfully carrying out this program lies with the placement officer himself.

The workshops, as we shall see, require not only men and services, but a physical plant, equipment, payrolls, orders, sales outlets, advertising, and all the other appurtenances of an industrial plant. Initially, these requirements could be successfully managed through an informal organization, but, as the size of the workshop increased, more formal methods of accounting, producing, selling, ordering, training, and billing had to be instituted. The workshops, therefore, came to be a social

service which had to be administered through a highly complex system of industrial organization.

From their inception both sheltered workshops and placement programs encountered problems. The basic problems of sheltered workshops were *(1)* the kinds of items they could manufacture were limited, because of commercial industry, to those having a small market and a limited margin of profit; and *(2)* the items that were selected had to be easy to manufacture because of the physical deficiencies of the workers. Consequently, the shops were forced to specialize in such items as brooms, mops, rugs, and cane chairs. Because the margin of profit yielded by these products was small, the shops had to manufacture a large number of them in order to break even. Shop employees, however, were largely persons who were incapable of competitive employment and whose rate of productivity was commercially inadequate. In addition to problems of production, there were problems of sales--of finding a market sufficiently large and reliable for their goods. Prisons, because they ordinarily manufactured the same items as workshops for the blind, were competitors for the market.

As a consequence of these economic circumstances, the shops were constantly operating at a deficit. This situation had been assumed from the outset, but no systematic, reliable provisions had been made for making up the difference. At first the state commissions tried to prevail upon the legislators to appropriate funds to make up the deficit accruing from the workshops, but the idea became increasingly less popular among legislators. This arrangement was not always welcomed by the workshops either, because it required constant negotiations with the frugal and sometimes capricious politicians. Many shops conducted annual fund raising campaigns to make up the difference, and in still other instances the workshops charged a price higher than the fair market value of their items. These problems of production, sales, and financial loss were constant thorns in the sides of workshop managers.

Programs of commercial placement of the blind experienced no less difficulty than sheltered workshops. First, the placement officer had to convince manufacturers that blind persons could work competitively in commercial factories if proper jobs were found for them. This procedure involved numerous difficulties, difficulties which were reported frequently at early AAWB meetings as a lack of public confidence in the blind. A second problem with the commercial placement program was that those who were hired as placement officers were themselves inexperienced and untrained. Because some were noted more for their enthusiasm than for their good judgment, errors in job placement were made. There was, however, a third and more serious problem with which placement officers had to contend. Usually the blind could do only unskilled labor in commercial plants. As we know, the demand for unskilled labor fluctuates with the economy: persons who occupy these positions are

ordinarily the "first to be fired and the last to be hired." Placement officers could not, therefore, assume that the jobs they had found for their clients were permanent. Despite the enormous investment of time and energy which was required to find jobs and to train persons to fill them, the placement officer usually had to assume that his client would occupy his job for only a relatively short period of time.

Still, in the pre-World War I period both sheltered workshops and placement programs did make some progress toward providing employment for the blind (7). By 1915 there were dozens of workshops (the exact number is difficult to determine because no regular census was taken) employing hundreds of the more severely disabled blind.

The first noticeable change in these conditions came about during World War I, which brought full employment for the labor force. However, the marked increase in buying power was accompanied by a marked decrease in consumer items because of the materials required to support an army. The effect of this, so far as the workshops were concerned, was a willingness on the part of the public to pay higher prices for blind-made products and to contribute funds as subsidies to the workshops. The larger deficit incurred by the general decrease in effectiveness of workshop employees (many of the skilled blind workers moved out into commercial industry) was more than compensated by increased sales at higher prices and by the greater possibilities of public subsidy.

The labor shortage created by the call to arms made it possible for any competent blind person to obtain a job in commercial industry. With the cooperation of workshop managers, placement officers placed many blind men and women in a wide variety of industrial positions. As the more capable blind persons moved out into commercial positions, vacancies were created in the workshops. These positions were filled by blind persons who ordinarily would not have been considered for any employment or who had been suitable candidates for home industries. The war, therefore, facilitated programs of commercial industrial employment of the blind and also enabled the workshops to fulfill more adequately the social service function of providing remunerative employment for severely disabled blind persons.

After 1918, employment opportunities for the blind reverted to a situation similar to the one before the war. Commercial industrial jobs for blind persons became more difficult to locate, and many of the blind who held factory jobs were laid off or replaced by returning veterans. As before the war, sighted persons were usually given preference over blind persons in hiring. As some of the less able blind persons retired or left the workshops, they were replaced by those who had been laid off from industry.

With the Depression employment opportunities for the blind inevitably collapsed. In commercial plants blind men were the

first to go. They were discharged not only because they were blind, but also because they held the kinds of positions ordinarily eliminated first in times of economic depression. As unemployed workers flocked to the agencies for assistance, they were referred to workshops for whatever jobs they could get. The workshops, however, were no better off. At the same time, the bottom dropped out of the market for their products, and they found themselves unable to find new products which could be widely sold. The policy of relying upon charitable impulses of the public as a means for selling products and for meeting deficits was now impracticable. People no longer had extra income to buy brooms and mops out of sympathy for the blind. Former commercial consumers of blind-made products were themselves out of business or no longer in need of very many workshop products. These cross-pressures forced workshop managers to concentrate less upon providing social services for their employees and more upon keeping the workshops alive. The "luxury" of providing work for industrial incompetents could no longer be afforded. Very basic economic problems had to be solved and solved quickly if the shops were not to close down completely.

The economic woes of sheltered workshops predominated in the discussions of AAWB meetings, and in articles in the *Outlook* during the thirties. Possibilities of new markets or of new products for the blind were constantly being rehashed. The employment prospects for the blind remained dismal. It was during this period, when workshops were fighting to stay alive, that a whole set of new sentiments began to emerge among workshop managers. How could shop managers reduce deficits each year in the make-work atmosphere which required them to pay a minimum salary regardless of production? During the early thirties there were simmering disputes regarding the proper function of the workshops. These disputes ultimately revolved around questions of management and employment--of how the shops should be run and who should be employed. These issues finally came to the surface in 1935, when a study was reported at the AAWB meetings by Mr. Edward Dowling, manager of a workshop in the New York metropolitan area. This study reflected the impact that the Depression had had on the thinking of workshop managers and the shifts in thought concerning the business aspects of sheltered workshops.

The findings were based on responses to a questionnaire mailed to 25 major workshops across the country. It inquired about the policies of the management concerning matters of employment and business. Mr. Dowling reported that "...the consensus of opinion of 25 employers of blind workers is that the maximum age at which workers should be hired should be set at 45 with an outside limit of 50 for exceptional men and women. When we take into consideration the months and even years that it takes to train a blind person to be a top notch producer, we realize that any higher age limit would tend *to reduce the years*

of usefulness to the workshop to such an extent that it might well be a losing proposition" [(8); italics, the authors]. He also observes: "Still another strong argument for *eliminating the incompetents* from our shops is the breakdown in morale of the whole force which is sure to follow if these incompetents are allowed to remain" [(9); italics, the authors']. Beginning with a philosophy of providing sheltered employment to those unable to work in competitive industry, the shops had arrived at a philosophy of discharging incompetent workers in order to be fair to competent workers and in order to be fair to the workshop itself.

The operation of the workshop, Dowling argued, should be governed by strict business standards--of efficiency, production and cost. Only competent workers were to be employed. He pointed to the possibility "...that the saving effected in reduced costs of operation will allow for the establishment of auxiliary craftshops in which the less skilled and less competent workers may be given employment and in which they might at least be partially self-supporting" (10). This suggestion was followed by some agencies, but profits more often went back into the workshops than to the special craftshops for which they were intended.

The strength of these sentiments is revealed in some of the letters returned with the questionnaire. One manager observed: "We are anxious to improve the character of workers and do away with the idea that our shop is a retreat for unemployable blind who foment trouble and do not want to produce anything" (11). Another person took the position that "the blind who are physically and mentally unable to produce sufficiently to take care of their needs should not be employed in a workshop whose *main object is producing marketable merchandise*" [(12); italics, the authors']. This position seems to imply that the shop should employ *industrial competents*--that is, the persons who in ordinary times worked in commercial industry. The seed of a nasty conflict between advocates of workshops and advocates of commercial employment for the blind was planted.

These sentiments of workshop managers were accompanied by a belief that anything that improved the economic position of the workshops was acceptable. To illustrate the extremes to which this view was taken, Mr. S. S. Catell, speaking to workshop managers at the 1935 AAWB meetings, asked the following question of shop managers: "Would it be advisable for this shop to employ a few extra broom makers *who have normal vision,* at times, when needed, to enable the shop to take larger orders, fill them promptly, and give better satisfaction to customers? The shops would then make a special effort to secure larger orders resulting in more employment for the blind worker" [(13); italics, the authors']. Catell was not alone in proposing this idea. Dowling had mentioned this matter in his own report: "In the consideration of the question of who shall be employed in sheltered workshops, some thought an investigation should be given to the hiring of more sighted workers in our shops. . . . Those who have put this policy

into practice say that production is speeded up, costs are kept down, and more blind workers can be put to work" (14).

These sentiments, and others equally strong, now began to pervade the discussions of employment at AAWB. In the meantime the voices of those who sought competitive industrial jobs for their clients faded into the distance. Economic conditions were as dismal as ever, and prospects of improvement were not very good. The papers read by placement officers were fraught with the frustrations of having no jobs for their clients and no promising leads to encourage them.

Concomitant with and complementary to this concern about who should be employed in the workshops was concern about available markets for blind-made goods. The problem was to provide a steady, predictable, and relatively lucrative outlet for the products. The basic economic platform upon which the sheltered workshops were to build was the Wagner-O'Day Act of 1937 which provided that "brooms and mops and other suitable commodities hereafter procured in accordance with applicable Federal specifications by or for any Federal department or agency shall be procured from such nonprofit making agencies for the blind" (15). A critical phrase in the wording of this act is "and other suitable commodities," for within six months of the bill's passage the workshops [working through National Industries for the Blind (NIB), an organization established by the workshops for the purpose of coordinating and assigning government orders to the individual workshops] added five additional commodities to the list, and within a few years this number was increased to 32 items (16). This act, along with 16 similar laws passed by state governments, provided the economic platform upon which the sheltered workshops could grow.

This legislation had the intended effect of guaranteeing the shops at least a minimum amount of business each year in standard inventory items such as mops and brooms. Since the government was now bound by law to buy the products that the shops made, so long as these products met its specifications, the shops had a guaranteed outlet for many more goods than just mops and brooms. It was now possible to diversify and expand operations, and consequently to fill up the deficit which the shops were annually running. The principal *unintended* effect of this legislation was brought about by the fact that the government expected the commodities of the workshops to meet in detail rigid specifications and to be delivered according to a time schedule. These specifications made even more urgent the necessity of hiring competent and efficient workers; only these workers could produce the items in accordance with government specifications. The employment of industrial incompetents became even more impractical. Moreover, the workshops were forced to accept a more stringent set of business principles. Since government contracts introduced a new predictability into the schedule of workshops, managers could now anticipate and plan production schedules as these came along. This in turn led them to run the shops in a more business-like

fashion than ever before. Consequently, the social service function for which the shops had originally been established was pushed further and further into the background.

The Wagner-O'Day act at first had only a modest impact upon the amount of business done by workshops. In 1939, government orders accounted for only about 10 percent of the total business of workshops participating in the program. Within one year the volume of government orders jumped from 10 to 50 percent of the shops' business (17). By 1943, 80 percent of all business done by the shops was devoted to filling government orders (18). The volume of business done with the government expanded as follows: in 1939, they did 1.9 million dollars worth of government business; by 1943, the figure reached 17 million dollars; by 1947, government business amounted to 40 million dollars. In 1943 alone, the volume was 10 million dollars, or more than five times the volume produced for the government in 1939. Moreover, increased industrial demands, coupled with the generally favorable economic conditions brought about by the war, helped contribute about half again the amount of business done for the government. In a period of five years the shops had become big business (19).

The economic boom during the war years, which brought about this acceleration of business for the workshops, had additional consequences for employment opportunities for the blind. When the war erupted in 1941 there was an acute labor shortage in the country. Employers sought every able man and woman for work in factories, shops, and industrial plants in order to meet production orders. One Brooklyn newspaper openly advertised for blind workers, guaranteeing them jobs (20). The head of one of the largest industrial concerns in the nation stated that there was a position in commercial industry for every blind person (21). A member of the Bureau of Placement of the War Manpower Commission addressed the 1943 AAWB convention concerning the need for blind workers in the war effort and the way to obtain commercial employment for them (22).

These circumstances gave the workshops an opportunity to return to their original function of providing social services for severely disabled blind persons. This opportunity was expressed in the 1941 AAWB convention by the Director of the Vocational Rehabilitation Division: "In view of the present emergency in which employers are clamoring for qualified workers, there is presented to all rehabilitation workers, and especially to the workers in the field of work for the blind, not only a golden opportunity, but also a challenge to do their part in seeing that every blind person, who is or can be made employable, finds his proper place in our efforts to meet the defense needs of our nation (23). This opportunity, however, was flagrantly ignored.

Faced with the prospects of expanded orders for merchandise from federal and state governments, and with an improved commercial market for blind-made products, the workshops began

to increase their production, drawing upon the pool of skilled and competent workers who had come to them during the Depression. The changing conditions were reflected in the enthusiastic statements of workshop managers concerning the business prospects of the workshops. In 1941, one manager told AAWB members: "Our workshops are now engaged in big business and they should conduct this business in accordance with the same principles as those observed in the management of private commercial enterprise" (24). Discussions at the 1941 and 1943 AAWB conventions largely consisted of suggestions of ways to implement formal procedures for running the workshops as "big businesses." One manager was moved to comment: "I want to come directly to the special significance which with the advent of war has come to the workshops for the blind. In a sense, it is a rather curious significance; curious in that it is new to the workshops, and perhaps as yet a bit unfamiliar. But it is also a great thing; and it may be summarized in these five words: you are doing 'big business'" (25).

Despite the generally improved conditions there remained a disparity between production and sales. The Director of NIB, Mr. C. C. Kleber, noted in 1941: "Our problem is not primarily one of production. It is a problem of sales and disposing of the products which the blind have made" (26). He illustrated this problem in the following way: "At one time, in the early part of the program, we could not make enough pillowcases to meet the government needs. The shops doing this work can produce over 20 million pillowcases per year whereas the government requirement only amounts to about 5 million. We have two workshops alone that can produce over 7 million pillowcases between them" (27). In an attempt to remedy this situation the services of a sales expert were retained. At no point, however, did the workshops have more orders than they could fill.

It seems reasonable to assume that if the shops were outproducing the markets, they would encourage their better workers to get jobs in commercial industry. If the essential problem of the workshops was the sale of their items, and not their production, one could adjust the balance of production and sales by encouraging the better workers to leave. This consideration, coupled with the philosophy that originally brought the sheltered workshops into being, leads us to ask: What efforts did shops make to find jobs for their more productive employees? What attitude did they take toward skilled blind men and women leaving for "outside jobs?"

A characteristic attitude--it received considerable support--was expressed by C. E. Mack, a placement manager, who remarked: "Without question, I am sure that the primary purpose of every worker for the blind is consideration for the welfare of his client. This being true, every effort should be made to secure for the client the type of work for which he is best fitted and which provides the greatest remuneration. One of the fundamental principles of economics is that labor always seeks

the highest bidder for its services--this is true of the blind as well as the sighted worker. We cannot, therefore, *blame the blind worker when he deserts the sheltered workshop for more lucrative employment*. . . . In my capacity as Placement Manager, I am responsible not only for the placement of workers in private industry but the employment of blind labor in the various departments of our own workshop, as well as in our concession stands. It is true *we have lost a number of our best workers to private industry*, but there has not been a general exodus such as that experienced in other cities and which has had such a crippling effect upon workshops, especially those engaged in filling Government orders" [(28); italics, the authors'].

The NIB itself was constantly being approached by industrialists making requests for skilled and able-bodied blind men and women. In relation to these requests Mr. Kleber, President of NIB, gave the following statement of policy: "Of late there has been much discussion regarding the placement of the blind in private industry. This is a service which should be provided by the individual agencies, and it is up to each to formulate its own policies in this connection. Any inquiries which we receive relating to placement are always referred back to the agency in the territory from which the inquiry came. We have tried to devote our efforts strictly to the field of production and merchandising of blind-made products, and we expect to continue this policy in the future" (29). This ostrich-like stance assured NIB that its supply of skilled workmen would go untouched, since the only men the agencies could offer were newly blinded persons who were untrained in industrial work. It is clear that the attitude expressed above by Mr. Mack, and which was shared by a considerable number of his colleagues, mitigated against the placement, by the agencies, of blind workers in commercial industry (30). This situation, consequently, takes the form of one great vicious circle regarding placement of the blind in commercial industry.

Two qualifications about this situation should be noted. First, some agencies and workshops did, in fact, assist blind persons in locating positions in industry. Second, many blind persons rebelled against the "establishment" and struck out on their own. The large exodus of blind persons which ensued ultimately forced workshops to modify their position.

In order to summarize the developments in the field of employment of the blind, it is necessary to recall the philosophy that was shared by the majority of workers for the blind when employment programs began, and that remains the professed ideology of agencies for the blind. The primary objective was and is acknowledged to be employment in competitive industry. Placement programs were set up in order to implement this goal. It was necessary, however, to have an alternative to this employment objective for those unable to perform adequately in competitive industry. Sheltered workshops were established as a *social service*, to give remunerative employment to those unsuited for

competitive industry. In addition to this social service function, workshops were expected to assist placement programs in any way they could. Business considerations were intended to be secondary to workshop managers.

The organizational requirements of each of these programs were very different. Placement programs demanded no capital investment. They required imaginative and knowledgeable placement officers acting as liaisons between the blind and the industries in the community. This type of program required only a small supportive staff of clerical help and a small expense account. The sheltered workshops, on the other hand, despite their necessary but subsidiary role in relation to placement programs, demanded capital investment and ultimately a large and complex organization. The workshops, as a consequence of their bureaucratic machinery, began to take on a life of their own. As their bureaucracy grew, it dominated more and more of the over-all employment program of the blind. Increasingly, the workshops received a disproportionate share of financial and other resources allotted to employment of the blind (31). In order to meet production quotas, workshops came to rely upon clients in placement programs as a source of labor. Ultimately, the shops opposed the objectives of placement programs by attempting to keep workers in workshops at a time when industries were openly advertising positions for them. This development largely vitiated the individual placement program and exacerbated the conditions that were responsible for the establishment of the employment programs in the first place.

The predominance of the workshops over the placement program cannot be explained simply by the economic circumstances during the Depression (when job possibilities for the blind, as for other handicapped groups, were virtually nil); nor by the continuing difficulty of finding suitable jobs in commercial industry. One point still remains to be discussed: namely, that the agencies for the blind to which the workshops are attached are also responsible for programs of commercial placement. In many cases the person responsible for commercial placement is also responsible for recruiting workers for the shops. In this conflict of interest the subsidiary role of the workshops (from the point of view of professed ideology) becomes obscured by the economic exigencies of the workshops, by the capital and personnel invested in them.

From time to time during the war some workshop managers expressed concern over the fact that the favorable conditions created by the war would not last forever (32). The time would come when government and private orders would be cut back, and the workshops would have to find other means of support. When the war ended, all of the workshops were faced with this problem. Three different solutions were tried. First, some workshops began to deemphasize the "big business" aspect which they had assumed during the war in favor of a rehabilitation program. The cause of this change of policy was the Borden-

La Follette Act of 1943 which provided federal funds for state and local agencies to rehabilitate and retrain blind and other handicapped groups. Some workshop managers saw in this program a source of income which could replace the diminished income from government orders and the commercial market. Mr. Harry Spar, vocational director of the Industrial Home for the Blind in Brooklyn, speaking before the AAWB in 1948 said: "The emphasis which this event placed upon the vocational training of the blind as well as the possibilities for the employment of the blind and of the weaknesses in the preparation for employment of large numbers of blind persons which were pointed out by the gratifying success of many placement services for the blind during the second world war brought home to many administrators of workshops for the blind the necessity of formulating principles and developing facilities and techniques for the rehabilitation of the blind which could realize the ideal of helping the blind to achieve the fullest physical, mental, social, vocational and economic usefulness of which they are capable. As a result of the recognition of this necessity, increasing numbers of workshops for the blind are experiencing a rapid transition from small and frequently substandard industrial establishments employing blind labor to well-organized and highly-developed rehabilitation centers" (33).

A second solution was to convert workshops from places of sheltered employment into regular industrial factories which employed blind persons. The purpose of these new shops--called production shops--was to provide an alternative to commercial industrial employment by creating a fully competitive factory specializing in employment of the blind. These shops not only fill government orders, but also subcontract work for local commercial industries. Prices for manufacturing goods are determined by "the fair market value" of these products. This fact gives the production shop some advantage over competition in commercial industry because the shops enjoy a nonprofit status. At the 1950 AAWB meetings, Mr. Carl Olsen, manager of such a workshop, described what he felt to be the advantages of this type of arrangement over regular industrial employment of the blind: "In the well-organized blind workshops barring unpredictable economic disorders, year-round employment is practically assured, whereas in commercial industry, employment quite often is seasonal and in the case of labor curtailment, the blind worker, being less versatile, is very apt to be among the first to go. The efficiently managed workshop. . . can afford to pay higher piece work rate or day labor rate for the work performed, thus offsetting, in a measure, the handicap of the individual. Specially constructed equipment and safeguards would still further enhance the blind person's earning power. In sighted industry, by comparison, the blind individual would have to adapt himself to the equipment at hand and accept the prevailing rate of pay. . . . In an industrial workshop the blind worker is competing at his own level so that when he does a better job than his fellow

worker, it gives him a definite lift to know that he can improve himself, increase his earning power and perhaps eventually, take over a job with greater responsibility. Everything in a well-organized workshop is created to minimize the blind individual's handicap. The staff has been trained to deal with blind people. In most cases, the workers are collectively producing completed articles which are sold under the agency's label. He can, therefore, take a just pride in the things he creates. By contrast, as an employee among sighted workers, his handicap must be brought home to him in many ways--in his contacts with co-workers, in the equipment he uses, in the facilities of the factory, etc. Unquestionably, in many cases, he realizes that he is just plainly being tolerated" (34).

A third solution was to revert to the original social service function and, as before, rely upon public subsidies to make up planned deficits. This solution was not popular and was seldom chosen by workshop managers. It more or less fell to the shops that were unable to obtain federal funds for rehabilitation or that did not have a large enough population of blind workers to draw a production staff from, to perform this function by default. No data are available showing the number of workshops that adopted each type of solution.

Programs of commercial employment of the blind have remained largely ineffective. Many of them never recovered from the conflict with sheltered workshops over blind laborers during the war. As noted earlier, moreover, the placement officer was often responsible for recruiting blind men and women for the agency workshops. Since workshops represent a large capital investment and commercial placement programs do not, priority is ordinarily given to the former when any question of client placement is concerned. These two factors, however, are only partially responsible for the general ineffectiveness of placement programs. Basic changes in the postwar economy represent the major factor. Automation has eliminated a large number of jobs requiring semiskilled and unskilled labor. The consequences for the blind have meant that: *(1)* factory jobs that they would ordinarily occupy are rapidly disappearing; and *(2)* a hard core of able-bodied persons who formerly occupied unskilled jobs are now unemployed and are competitors with the blind for scarce and unstable jobs.

Their inability to obtain jobs for blind persons is attributed by workers for the blind to public ignorance about the work potential of blind workers, not to economic conditions. Because of this moralistic formulation of the problem, some employment specialists have adopted the view that the only sure way to guard against unemployment among the blind is to press for more preferential legislation similar to the earlier use laws. The most notable example of this is the Randolph-Shepard Act, which reserves for the blind vending and newspaper stands in government buildings. From time to time attempts have been made to obtain similar legislation in civil service positions, but these attempts have been much less effective.

The present status of employment for the blind is very difficult to assess. There has developed a considerable preoccupation with physical rehabilitation as a necessary precondition for vocational training. In addition, much is made of techniques of measuring vocational potential, individual aptitude, and so on. These techniques are for the purpose of implementing the goal of employment for the blind. A question that has not been raised, however, is this: The goal of employment of the blind was originally formulated in the context of a nineteenth-century economy. Does this goal continue to be realistic or meaningful in the context of the twentieth century automated economy where unemployment is an increasingly serious problem?

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31. It should also be noted that the workshops at one point came into open conflict with their parent agencies because the subsidies which they received often detracted from the public funds available to the agencies. See Joseph Clunk, *AAWB*, 1957, p. 14.

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A SOUND-SOURCE BALL FOR BLIND CHILDREN

Woodie Flowers

Since 1959, the Sensory Aids and Prosthetics Project of the Engineering Projects Laboratory and Department of Mechanical Engineering, MIT, has involved undergraduate and graduate students, under the supervision of Professors Dwight M. Baumann, Robert W. Mann, Thomas B. Sheridan, and W. Russell Ferrell in a succession of projects applying engineering research and development to the definition and creation of technology-based assists to the blind.

The work can be categorized into research on perception exploring the alternative tactile and aural channels still available to the blind, research on blind mobility and the development of devices to enhance the travel of the blind, and research on and development of means of increasing the blind's access to the printed page and other written communication.

The sensory aids effort is complemented by research and development on limb and skeletal prostheses and ortheses. Since the research interests of both programs overlap and reinforce each other, and both involve some of the same personnel, facilities, and support, a single bibliography combines both sensory aids and prostheses publications.

For most of the studies the basic resource document is the original Bachelor's, Master's, and Doctoral theses, available for reference or photocopy in the MIT Library or by ozalid copy from the EPL Document Room, 3-156, MIT. Papers published in the journals of professional societies and organizations also represent a source of fundamental and interpretive information on the program. For investigations that have not culminated in either thesis or professional publication, Engineering Project Laboratory reports are prepared and circulated, as for example, this report, A Sound-Source Ball for Blind Children. *The bibliography appended to this report lists the title, author, and source of all theses, papers, and reports prepared by members of the Sensory Aids and Prosthetics Group.*

Major support for the program has been provided by the Vocational Rehabilitation Administration of the Department of Health, Education and Welfare. Supplementary grant-in-aid support from the American Foundation for the Blind, the Medical Foundation, Inc. of Boston, and the E. Matilda Ziegler Foundation of New York City are also gratefully acknowledged.

Robert W. Mann
Professor of Mechanical Engineering

BALL SPECIFICATIONS

The purpose of the work outlined in this report was to construct a sound-source ball to be used as a training aid and toy for partially and totally blind children. The general statement of the problem and specifications for a prototype ball were taken from previous work done by Mr. Ronald Rothchild. (*Design of a "Talking Ball" Sensory Aid for the Blind*, S.B. thesis.) Essentially the objective was to construct a ball that would produce a loud sound; not be so hard that it would injure the children; endure being bounced, kicked, and batted; and be approximately the same size and weight as a basketball.

In order for a sound-source ball to be effective, it is necessary that the ball behave as a spherical sound source--that is, the sound be transmitted through the entire surface of the ball, not just be emitted from several points on the outside of the ball. This requires that the skin of the ball be thin enough to allow transmission of sound from an internal source. The entire weight of a standard basketball is the weight of the thick shell or skin. If a sound source is to be added inside a ball and the same weight maintained, obviously a very light material must be used for the skin.

These restrictions specify that the ball have a thin, lightweight skin inside which is suspended the most significant part of the mass of the entire ball. Therefore, in order for the ball to behave in a regular manner when bounced or thrown, the inertance and kinetic energy of the sound source must be communicated to the surface of the ball in an almost perfectly symmetric and elastic manner.

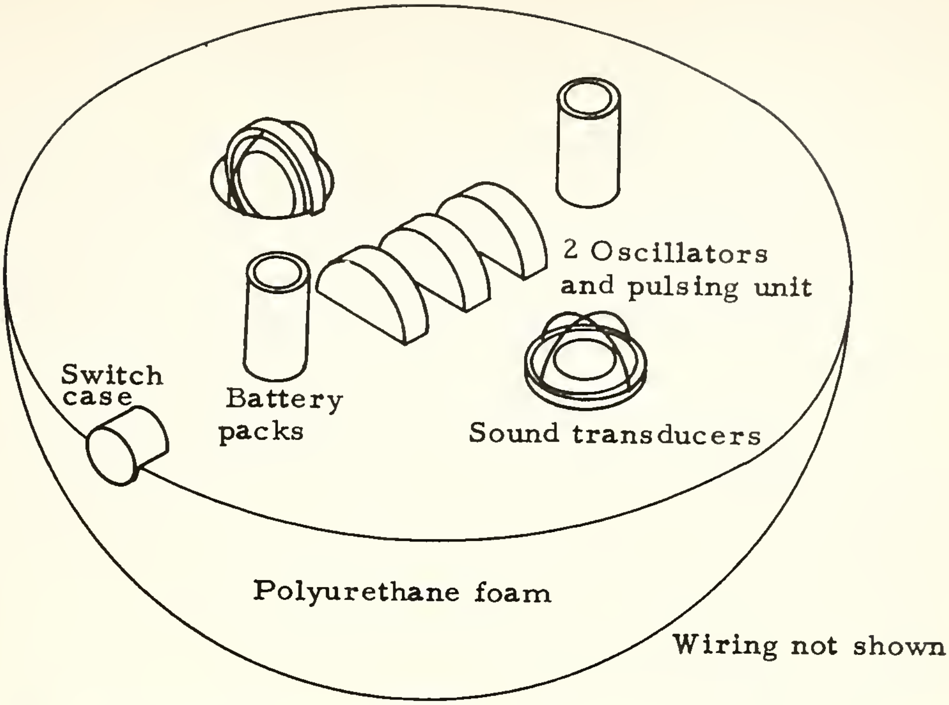
Sound derived from the motion of the ball is considered undesirable because a sighted person would have to recover the ball each time it rolled to a stop during use. If mechanical energy storage were used to maintain the sound for an appreciable period after the motion of the ball stopped, the energy absorption of such an element would probably significantly effect the dynamics of the ball. Because of the low weight-to-energy storage and power output ratios available, batteries and electronically driven transducers were used for the sound source.

Problems encountered in previous attempts to suspend the sound package in the center of the ball by tension members attached to the skin prompted an effort to develop a different technique for suspension of the sound source.

BALL DESIGNS

Foam Core Centrally Located Components

The first technique investigated was the suspension of the sound source in the center of a polyurethane foam sphere as illustrated in Figure 1. This sphere fits tightly inside a bladder and an inelastic skin.



Distribution of sound source components in foam sphere

Foam sphere without bladder and skin

Figure 1. Foam Core Ball

Rogers Foam Company of Somerville, Mass., was contracted to make three 10-inch diameter, polyurethane foam spheres. Hemispheres were made by rotating an electrically heated, semicircular wire through a block of foam as shown in Figure 2. One sphere was made from 10 pore/inch foam, one from 40 pore/inch foam, and the other from 80 pore/inch foam. All three foams were 97 percent void. The weight of each sphere was 8-1/2 ounces. The cost of the three spheres was high because of the tooling necessary to produce them. However, in larger numbers the spheres could be produced for less than five dollars each.

At the frequencies produced by the sound source, the 10 and 40 pore/inch foams caused very little attenuation, while the 80 pore/inch foam reduced the sound level noticeably. The 40 pore/inch sphere was used for the ball described.

In order to distribute loading of the foam when the ball is bounced, the components of the sound package were separated and placed apart from one another in the central part of the ball. Using preformed, heated wires, holes were cut into the face of each hemisphere forming sockets into which the components could be placed. In the face of one hemisphere 1/4 inch x 1/4 inch channels were cut to accommodate the wiring.

Goodyear Pliobond was used to glue the components in place and glue the hemispheres together.

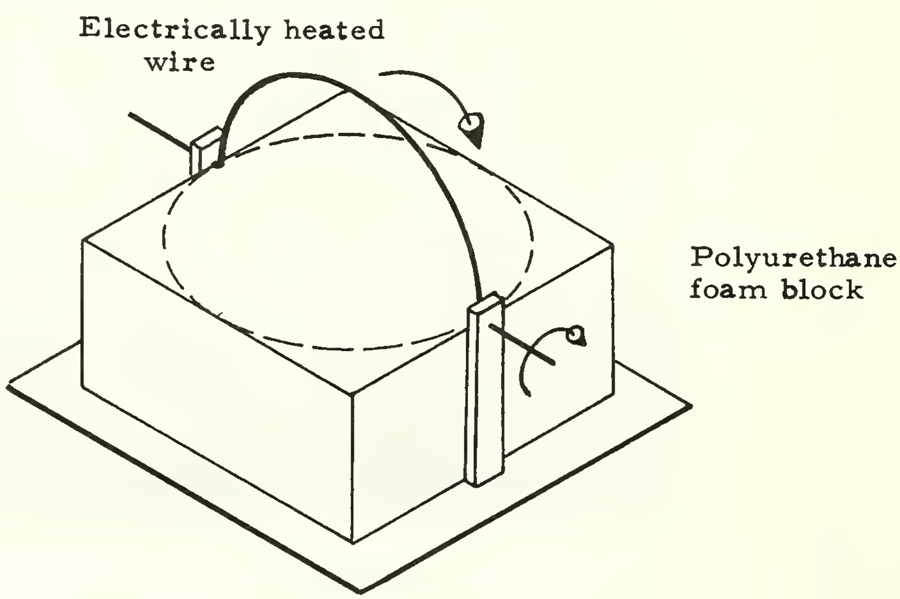


Figure 2. Production of the Foam Spheres

Mallory "Sonalert" components were chosen as a prototype sound source. These devices are compact, audible alarms in which a loud sound is produced by a ceramic transducer oscillating at its natural frequency. The units are rated to withstand 600 g's. The specifications for the two units used are

Catalog number	SC 628P	SC 628H
Supply voltage	6-28 D-C	6-28 D-C
Sound level	68-80 db+	68-80 db
Current	3-14 ma	3-14 ma
Weight	2 oz	1.25 oz
Frequency	2,800 cps	4,500 cps

+Pulsating 3 to 5 cps

The 2,800-cps pulsating unit was disassembled to yield a pulsing oscillator, a 2,800-cps oscillator, and a piezoelectric transducer. The 4,500-cps unit was separated into a transducer and a 4,500-cps oscillator. These components were rearranged as in Figure 3.

Two frequencies were used to reduce the pure-tone echo effects that can give a false indication of the location of the ball. A pulsing sound source is considered desirable because it uses less power and allows the user to take advantage of Doppler effects. The result was a "chirp" approximately 4 times per second.

Since the entire sound source was to be inside a pneumatically sealed container, rechargeable batteries were chosen to avoid complicated battery replacement procedures. Each of the two battery packs consist of ten Burgess CS-2 nickel-cadmium cells stacked in series inside a thin-walled, plastic-impregnated, linen cylinder. This provided 20 mah at 24.4 volts (enough to operate the sound source for approximately 14 hours).

The transducers were mounted inside piano wire cages to prevent their contact with the foam. (See Figure 4.) As illustrated in Figure 5, the wires were coiled and placed in channels to insure that the connections would not be pulled loose when the ball is deformed. All connections were soldered and covered with drops of epoxy. Size 30 multistrand insulated wire was used.

A type 850 microplug and a type TR2 microjack serve as an "on-off" switch for the sound source and a charging terminal for the batteries. When the charging plug is removed from the jack, the sound source is turned on. A detail of the installation is shown in Figure 6.

The weights of the parts of the sound package are given below:

Battery pack	1.23 oz
2,800-cps oscillator	0.67 oz
Pulsing unit	1.00 oz
4,500-cps oscillator	0.92 oz
2,800-cps transducer	0.18 oz
4,500-cps transducer	0.29 oz

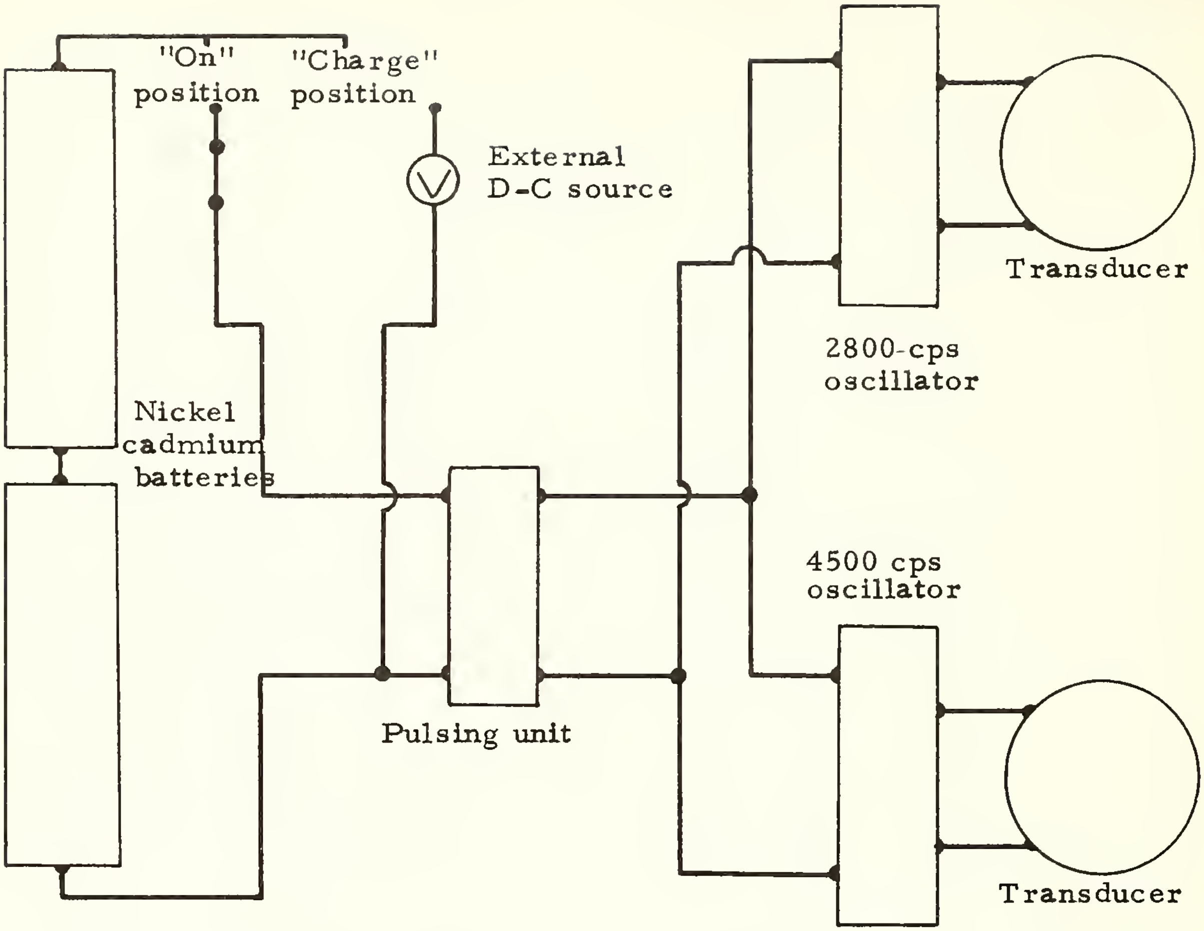


Figure 3. Block Diagram of Sound Source

The skin of the ball was fabricated by Sawyer Tower Products, Inc., Watertown, Mass. The material used was developed for extremely tough, lightweight foul-weather apparel. It is polyurethane-coated nylon produced by Sawyer Tower and has the trade name Super Rhino-Lite. The ball skin was cut and sewn as illustrated in Figure 7. The pattern was developed for a 9-1/2 inch diameter ball so that the 10-inch foam ball would always remain in contact with the skin. Bright yellow material was used.

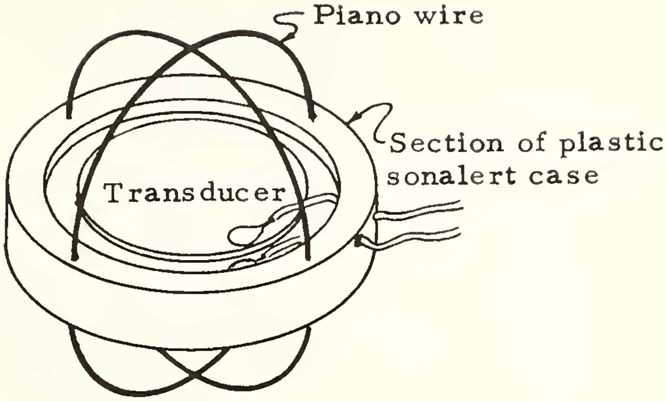


Figure 4. Transducer Mount

Test showed that the thickness of the bladder had a significant effect on the attenuation of the sound. Also, it was found that the attenuation varies with the tension in the bladder; therefore, a thin, tightly-stretched membrane would be optimum. Thin toy balloons were satisfactory except for their poor quality. In some cases a balloon would fail for no apparent reason. However, a more expensive and slightly thicker balloon seemed to solve this problem.

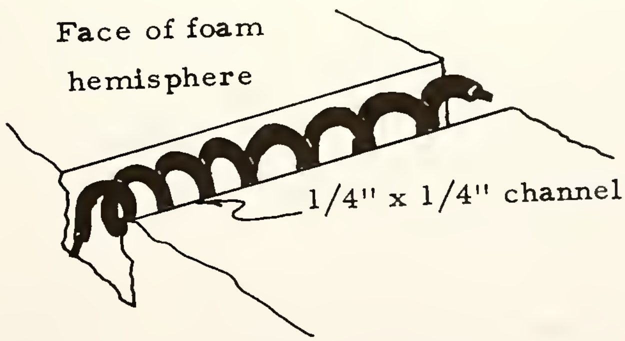


Figure 5. Wiring Channel

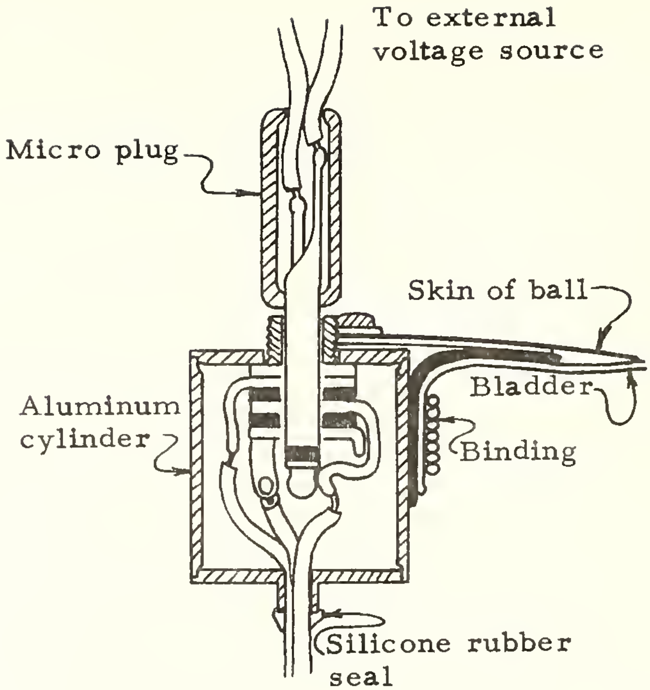


Figure 6. Sound-Source Switch and Charging Terminal

The assembly of the skin, bladder, and foam sphere containing the sound package was complicated and would increase the cost of the ball as well as make repairs difficult. In order to get the 10-inch sphere through the neck of the balloon, the sphere was first pressed into a large can (approximately 6 inches in diameter) which had had both ends removed. The neck of the toy balloon was then stretched over one end of the can, and the neck of a large weather balloon over the other end. Through a hole in the side of the can, both balloons were inflated. The foam sphere was then pushed out into the toy balloon. After the neck of the toy balloon was removed from the can, it was plugged with the cylinder surrounding the charging terminal. A small hole was cut into the other end of the balloon, and the inflation port was installed as in Figure 8.

The entire package was then placed inside the nylon skin and the last seam hand stitched.

The ball was inflated to 7 psi. Although the skin had been made spherical, as the ball was pressurized the seams stretched, and the shape became somewhat oblate. The output of the transducer was attenuated approximately 40 percent on the skin and the bladder. The sound emitted from the ball was almost completely nondirectional.

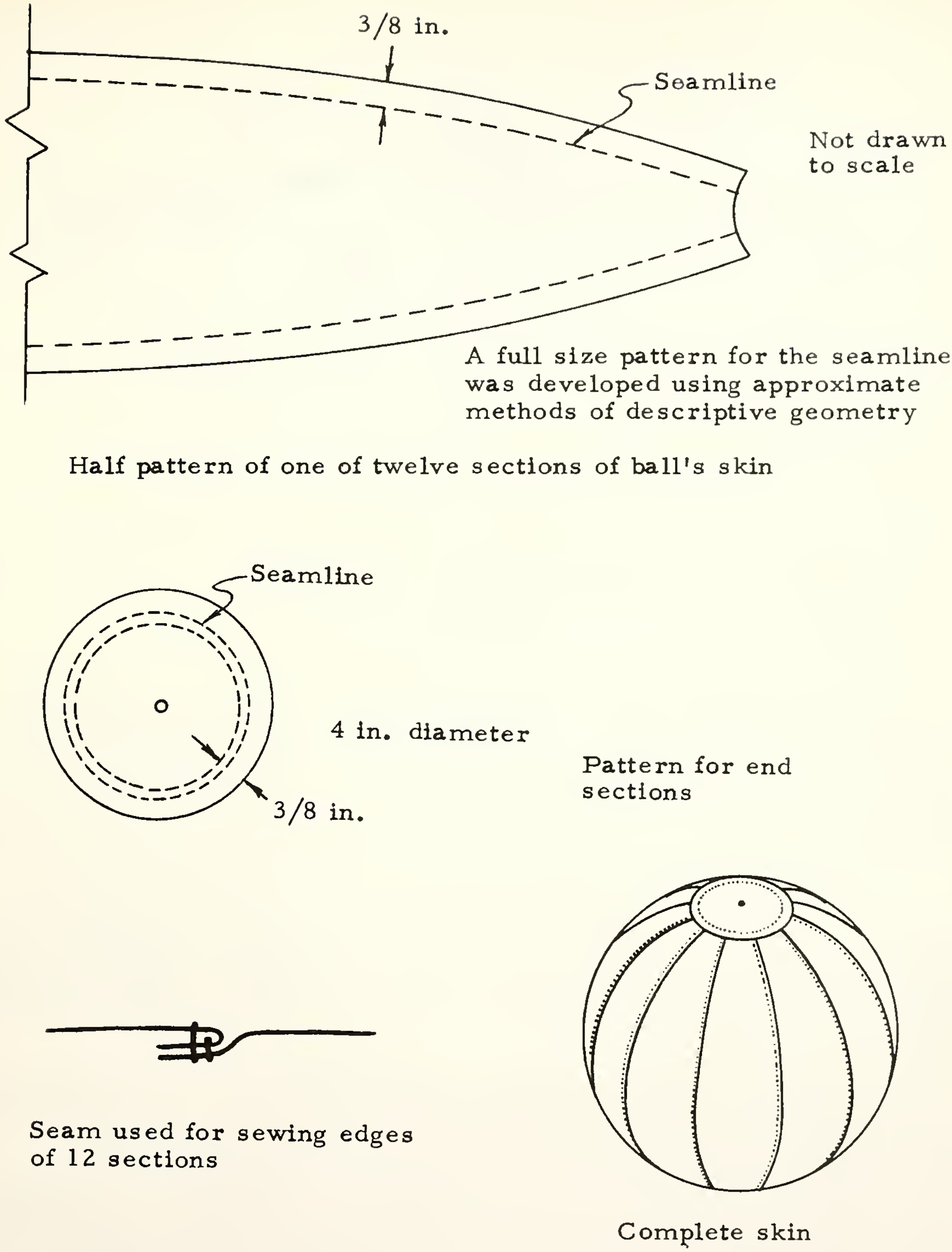


Figure 7. Details of Ball's Skin

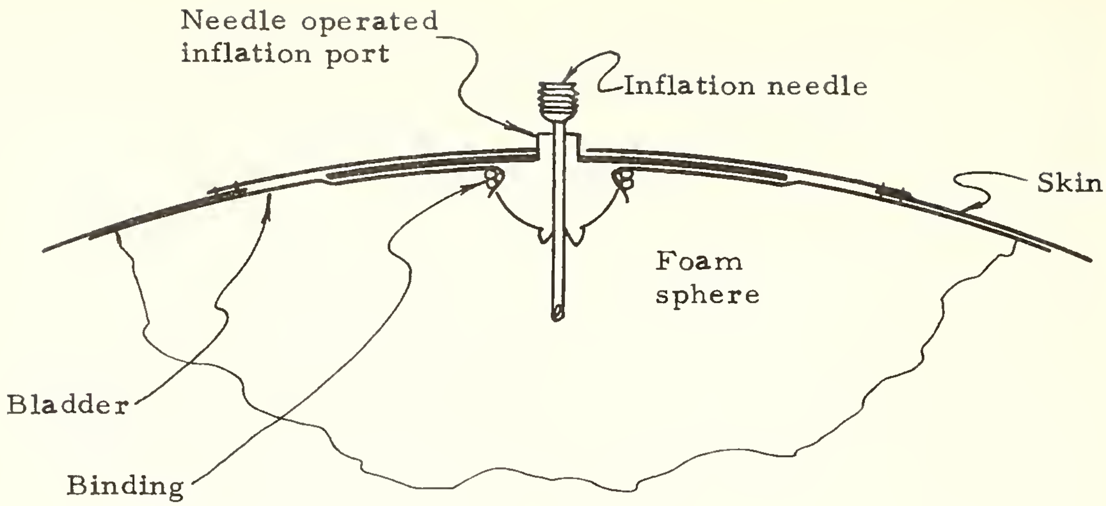


Figure 8. Inflation Port for Foam Core Ball

The most important limitation of this ball was the coefficient of restitution. Even when fully pressurized, the coefficient was less than 1/3 when the ball was dropped 6 feet. Apparently the energy losses associated with deforming the foam at the contact spot and due to the motion of the components relative to the skin during impact were sufficient to overdamp the motion of the ball.

The ball weighed approximately 16 ounces and had good balance. It withstood being kicked, bounced, and thrown forcefully into walls. This design of the ball might be satisfactory for games in which resilience is not important. However, the complexity of producing and repairing such a ball would probably make it impractical.

Multiple Bladder Centrally Located Components

The second type of construction tested is illustrated in Figure 9. This type consisted of two separate hemispherical skins with the sound package placed between them.

The dynamics of this configuration were intolerable. The ball behaved very unpredictably, making it useless to a blind child. The dynamics could have been improved by separating the ball into many compartments. However, making such a ball spherical when all the compartments were inflated would be very difficult, and the cost of manufacturing would be prohibitive.

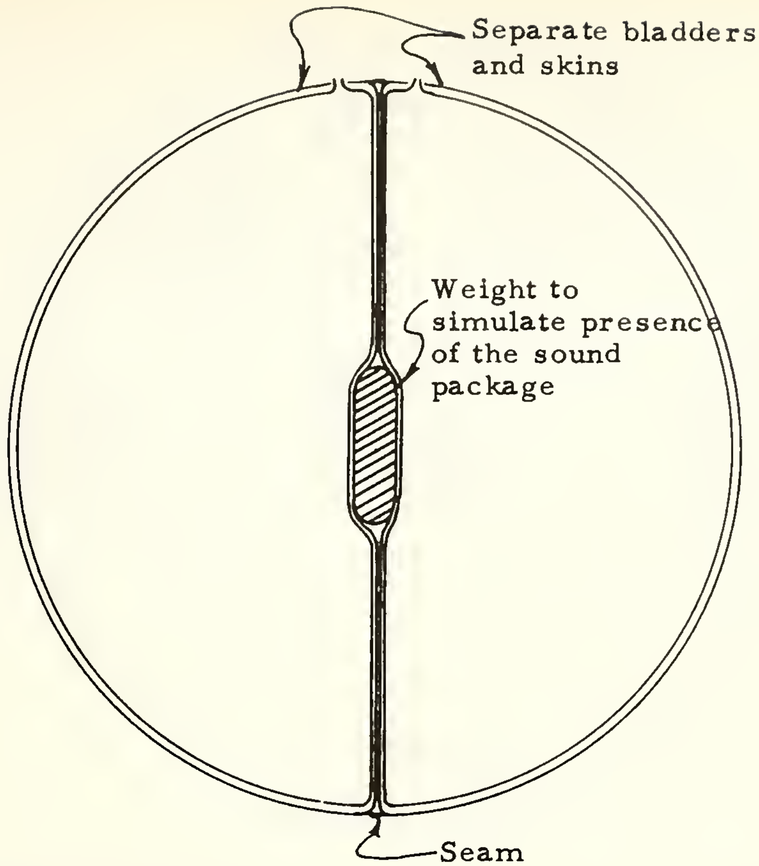


Figure 9. Multiple Bladder Ball

Shell Supported, Distributed Components

The third design is illustrated in Figure 10. This approach divides the sound package into six parts of equal mass, affixes these components to the top of foam rubber pads, and arranges them on the inside of the ball's skin so that the ball will be dynamically balanced. The pads and components are held in position by the pressure in the bladder forcing them against the inside of the ball's skin. The sequence in Figure 11 shows how the shape of the ball changes as the bladder is pressurized. It can be seen that even though the components and pads protrude into the ball as much as 2 inches, as the pressure forces the bladder to conform to the shape of the protrusion, the outside of the ball assumes the shape of the inelastic skin.

The sound source used in this ball is essentially the same as the one used in the foam-filled ball. A block diagram is shown in Figure 12. In order to reduce the weight of the pulser and oscillators, some of the epoxy encasing these components was removed. The transducer cases were redesigned to

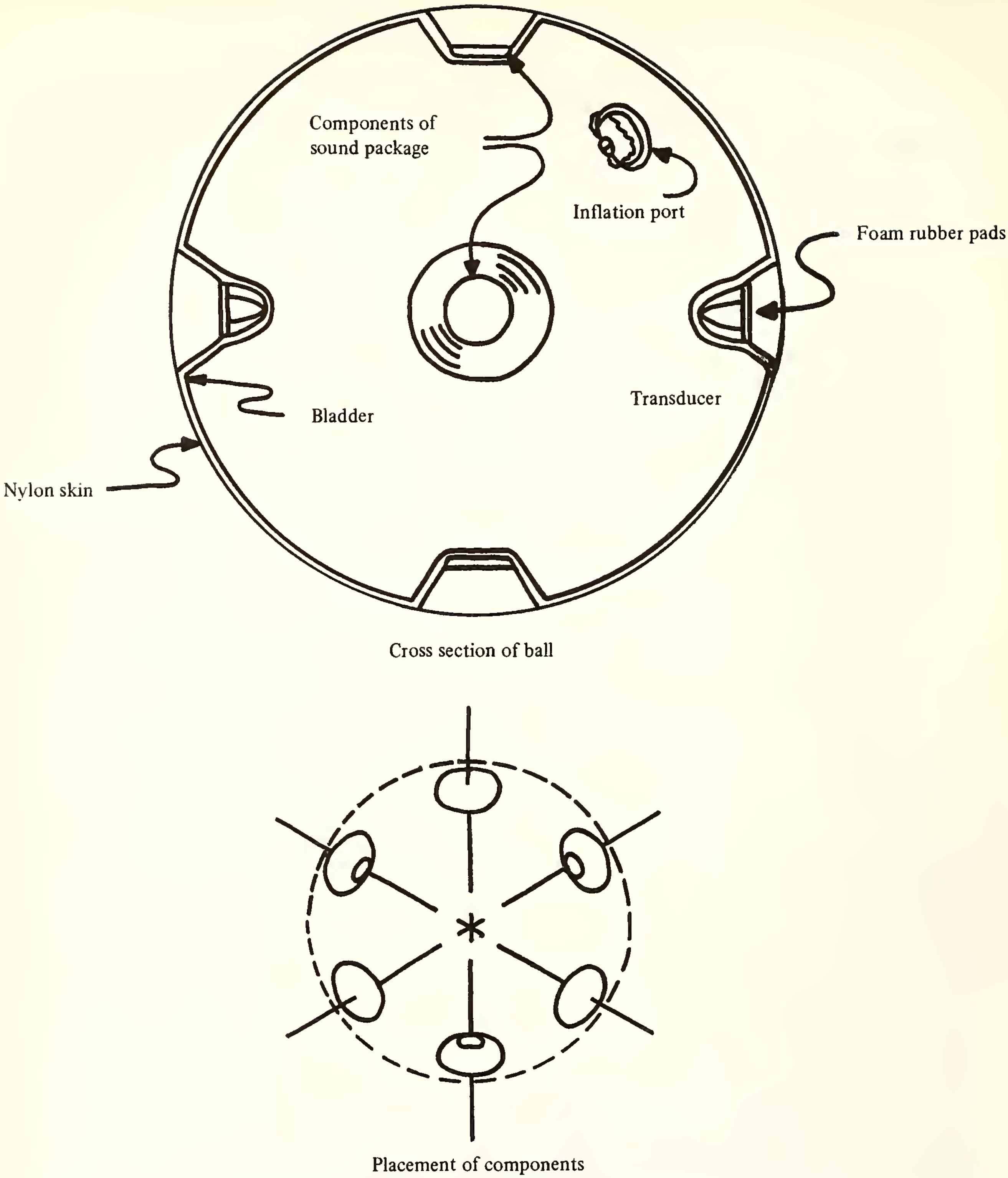


Figure 10. Details for Shell-Supported, Distributed Component Ball

prevent the bladders from touching the transducer. All connections were soldered and covered with silicone rubber.

Since this ball has a zipper, a replaceable battery was chosen. The battery case was mounted near the zipper opening such that the battery could be replaced by partially deflating the bladder, unzipping the skin, replacing the expended battery, closing the zipper, and then reinflating the ball. A 22-1/2 volt Burgess U-15 battery was used. Life tests showed that this battery would operate the sound source continuously for 16 hours.

The same type switch was used to start and stop the sound source--that is, when a microplug is removed, the sound source is on. The weights of the components and their pads are

22-1/2 volt battery, case, and pad	1.95 oz
2,800-cps transducer and pad	1.37 oz
2,800-cps oscillator and pad	1.48 oz
4,500-transducer and pad	1.41 oz
4,500-oscillator and pad	1.44 oz
Pulser and pad	1.51 oz

a. Partially inflated ball   b. Fully inflated ball (5 psi)

Figure 11. Shell-Supported, Distributed Component Ball

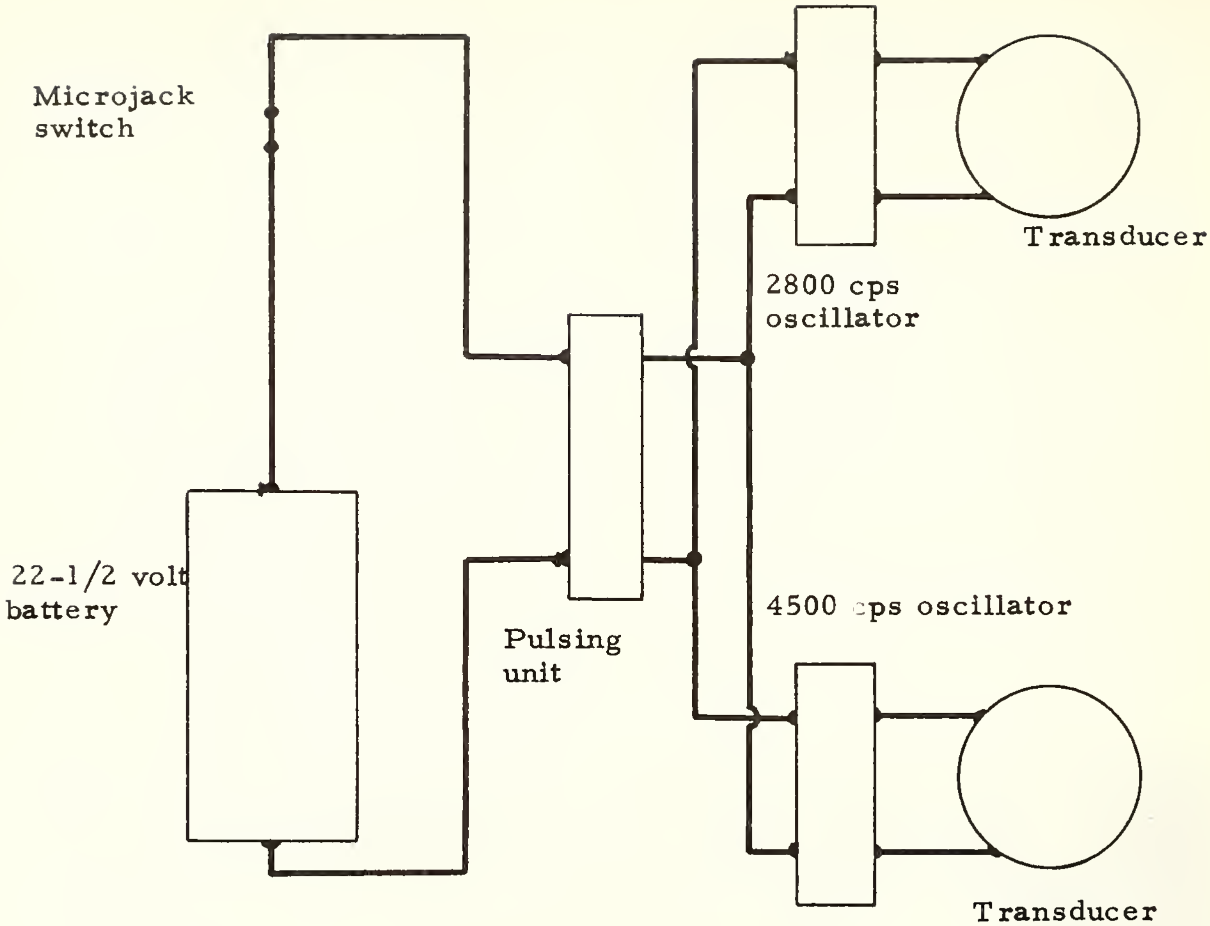


Figure 12. Wiring Diagram

The foam rubber pads were cut from a 1-inch thick sheet using standard hole saws operated at high speed. The pads were tapered by spinning them on a mandrel and shaping them with an Exacto knife. The battery case pad was cut roughly to shape with a sharp knife lubricated with water and finished using a belt sander. Figure 13 illustrates the importance of tapering the pad in such a way that the skin of the ball will not be deformed.

The skin was made of the same material as that of the first ball, and a similar pattern was used. The pattern was developed for a 10-inch sphere and 1/32 inch was taken off each side of the pattern in the middle to compensate for the stretch of the seams. A 7-inch Talon nylon zipper was installed alone one of the seams. A cover was sewn over the ends of the zipper such that the zipper tab could not be moved until the ball was partially deflated.

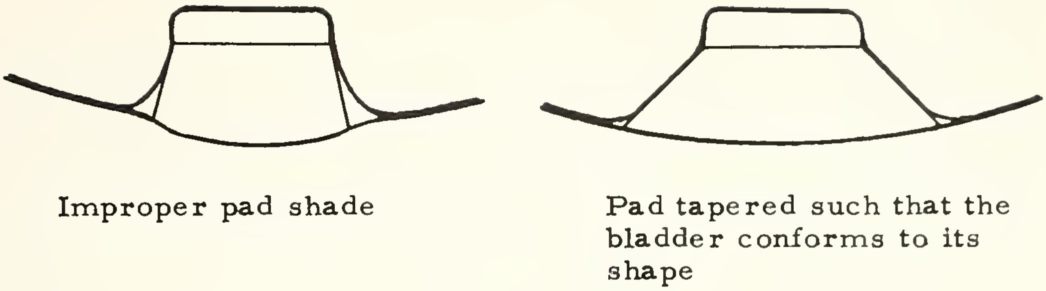


Figure 13. Component Pad Shape

A toy balloon served as the bladder and was connected to an inflation port in the same manner as in the foam filled ball.

To assemble the ball, the skin was turned inside-out and a balloon inflated inside to tighten the skin. (See Figure 14.) The pads were glued to the skin with Pliobond, and the components were inserted in the tops of the pads. The size-30 multistrand wiring was also glued in place against the skin.

Figure 14. Distributed Component Shell Supported Ball Inside-Out During Construction

The balloon to be used as the bladder was then attached to the inflation port. The temporary bladder inside was deflated and removed, and the ball was turned "right-side-out" through the zipper opening. Before the zipper was closed, talcum powder was put inside the skin to serve as a lubricant for the bladder.

As can be seen in Figure 11b, the ball is almost spherical when inflated (the pressure in the ball was 5 psi when the picture was taken). When the ball is bounced such that the contact area does not include any of the component pads, the coefficient of restitution is approximately 0.6. When the ball is impacted directly on one of the pads, the bounce is slightly less. When the contact circle passes through one of the pads, the ball is deflected somewhat. However, the ball responds as good as, or better than, a standard basketball, and the bounce deflections are not of sufficient magnitude or frequency to prevent the ball from being dribbled. Even though the dynamic balance is not perfect, the ball can be tossed into the air while spinning about any axis with no noticeable wobble Apparently, exact balance is not necessary to make a ball behave acceptably. The total weight of the ball is 12 ounces. It has the same rigidity as a basketball and responds as if its mass is continuously distributed.

The sound level is slightly less than that of the foam filled ball because the sound must be transmitted through the bladder twice. The sound emitted from the ball was almost completely nondirectional.

The only failure thus far has been in the battery case. The plexiglas case cracked and allowed the battery contact to move. Making the case of a material such as hard rubber would eliminate this problem. The ball was repeatedly thrown against a wall, bounced very hard, and kicked with the toe of a shoe. In one of the tests the ball rebounded against a sharp metal corner which cut a 1/8-inch hole in the skin. However, the nylon material is woven in such a way that a tear will not propagate; therefore, the ball did not rupture. The ball supported 200 pounds without damage.

These tests indicate that a sound-source ball made in the manner described could endure the punishment expected in most types of sports. Probably the most serious limitation of the life of the ball will be the skin's resistance to abrasion. Since the skin must be thin to allow the transmission of sound, it will be difficult to produce a ball that would last several years under moderate-to-heavy use.

Initial Evaluation

Under the direction of Mr. A. Claude Ellis, Principal of Perkins's Institute for the Blind, Watertown, Mass., the ball was tested by a group of totally blind female students (estimated ages 10 to 14). Initially, the girls were given only the

instruction "Play with it." As the sound source was started and the ball was bounced on the floor before the group, the girls very enthusiastically grabbed for it and began competing to find the ball. Some of the students exhibited much greater ability to locate the ball than others. Mr. Ellis said that some of the girls had received more training in the use of auditory cues and that this sort of difference in dexterity should be expected. After several minutes of random play, the enthusiasm of the girls began to decrease. At this point an instructor asked the girls to stand with their backs against one wall of the gymnasium. The instructor rolled the ball toward one of the girls to see how she responded to it coming toward her. This experiment very clearly illustrated that the sound was not loud enough. In most cases, the girls would not start to reach directly toward the ball until it rolled within five feet of them.

The ball's bright yellow color is very appropriate since partially sighted children participate in most games.

RECOMMENDATIONS

The shell-supported, distributed component ball has several very desirable features. The fact that none of the electronics must be placed inside an air-tight bladder makes the manufacture and repair of the ball easier and cheaper. Repairing a rupture would not be difficult because the bladder used in the prototype ball was a ten-cent balloon, and cuts in the skin of the ball are easily repaired with a needle and nylon thread. The components are held in position by the pressure of the bladder; therefore no problems arise in attaching the components to the skin. The component suspension is continuous in every direction rather than composed of several high-stress point connections. The total weight of the prototype was less than a standard basketball; therefore additional strength or sound source power can be added without making the ball too heavy. Also, all of the materials used in making the ball are commercially available and not excessively expensive.

These advantages and the results of initial test and evaluations indicate that only relatively minor changes are necessary to produce an acceptable, second-generation ball to be evaluated in the field.

The sensory aids evaluation and development center could start a development program by constructing several (5 to 15) balls and placing them in selected schools for the blind. The sound level could be sufficiently increased by mounting an extra transducer beside each of the transducers presently employed. This would increase the power requirements, but would not overload the oscillators and would allow eight hours of continuous operation on the battery. This program would not necessitate manufacturing special castings or electronics and would yield useful information for refining the ball for production in larger numbers.

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TOWARD AN IMPROVED OPTOPHONE—EXPERIMENTS WITH A MUSICAL CODE

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Abstract

An early form of simple reading machine, the optophone, has been exhaustively experimented with by workers throughout the world. It has been a general finding that this machine fulfills the requirements of cheapness and portability, both of which are needed with a "personal" machine; however it also has been true that reading English text with it is so exceedingly slow and difficult that all but a very few talented blind people are completely deterred from using it. Remarkably little effort has been devoted to investigating methods for improving it. A potentially rewarding field has been left untouched by engineers and psychologists alike. This paper is concerned with the possibilities of improving the optophone.

A "musical" code, still easy to instrument, has the desired features of leading to a pleasant but not very (subjectively) complex sound. Sounds are produced that are actuated by the upper-lying boundaries of the letters only. Information of letter width is discarded. Certain general features of print letters can be recognized. Vertical and sloped straight lines are easy; repeated or symmetrical print shapes--for example, the letter W--are again coded by a characteristic sound; the code is weakest at representing curves. But identification into quite a small number of classes is possible. In its final form the code physically employs two dimensions of loudness and frequency. The patterns produced by the frequency variable are identified by the subjects into six groups.

Field tests were designed using sighted students and three blind subjects recommended by the Perkins School for the Blind. After forty to fifty hours of training, done mainly by the subjects in their homes and with tape recordings of sounds produced by a computer, they had read through material involving 260 words, and the words were presented at a word rate of forty per minute. It must be emphasized that only short phrases and short sentences were used.

1. INTRODUCTION

The problem of helping the blind to read has been studied for nearly 200 years. In 1786, Huay (20) suggested the use of raised letters in a treatise addressed to the king of France, and this suggestion led through evolutionary stages to the present-day raised dot print system, braille, which is used extensively by blind readers. (It must be remembered, though, that for one reason or another only 10 to 15 percent of the blind are able to use braille.) But the problem of making a machine that can translate ordinary print information, say in a book, into a form that can be assimilated by the blind has not been solved. The optophone has been experimented with since its invention and a large amount of effort has been expended in order to determine whether this machine will be of practical use to the blind. A qualified no seems to be the answer. The optophone can inspire tremendous and lasting affection from a very few peculiarly gifted people. But many potential users are discouraged by the slow reading rate ultimately possible. The machine is tricky to set up, it will not hold its adjustment, and adjusting the scanning slit to follow a line of print is practically impossible. Despite these drawbacks, one hears from time to time of newly blind people who say they are prepared to use the machine, and it is this pressure from the blind themselves that must be reckoned with. The optophone machine produces a code output which has to be learned. Surprisingly, the blind enjoy making the effort of learning; it adds to their skills and enriches their way of life by adding to their command of the environment.

A large amount of effort has been used to evaluate optophone performance but there has been surprisingly little applied research into methods for improving the machine. The small number of photosensors used in the optophone is largely responsible for the trickiness of the machine adjustments. Apart from economy there is a perfectly good reason why more photocells should not be employed: the complexity of the output signals. It is the author's opinion that such variability can, to all intents and purposes, be eliminated by increasing the photocell number and, at the same time, altering the decoding process. When this is done, a main stumbling block to the use of the optophone is removed. (Details of the proposed changes are given in section 2.)

The reader of a book is the "receiver" in a communication link between himself and the author. A number of processes link the information from the author with the perception of information of the reader. These are shown in the model of Figure 1. In Figure 1a we have the "transmitter" in which the author's information

Note: Dr. Beddoes advised us in May, 1967, that "We are continuing here. I am using a computer to prepare training tapes, and we plan to start a 300 hour per subject training program this month. I think this will take a year to run. After this time I hope the subjects will be able to read up to Grade 4 English (vocabulary 2500 words). I plan to build a number of the Lexiphone machines."

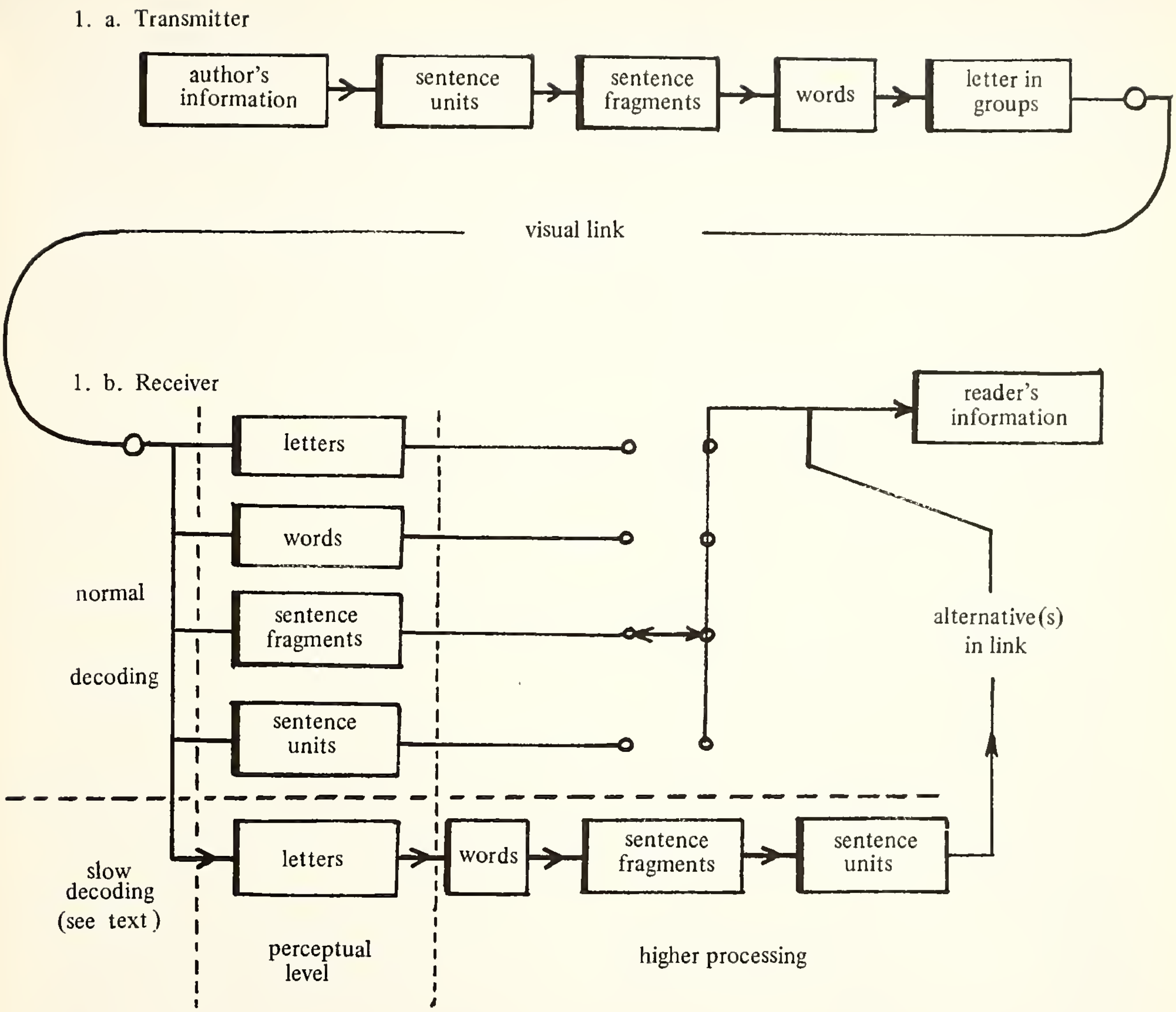

Figure 1. Model of Author to Reader Communication System

is transformed (by him) into a number of progressively more and more basic elements represented by the boxes, sentence segments, words, groups of letters. It is these groups of letters *only* that the reader obtains from the printed page, and a similar set of transformations proceeding in the reverse order must take place in order that the information be recovered by him. These transformations can take place along two roughly parallel paths for sighted readers. Thus, if we see succeeding letters one at a time, we can with a great deal of effort, and extremely slowly,

construct words from the groups of letters and construct the word units into sentence fragments and the fragments back into information. Reading normally, though, the reader is able to assimilate in parallel fashion word units and sentence fragments, at a single "look." With the more common-type words and more commonplace information, one can anticipate whole sentences and merely correct these anticipations by monitoring the odd word or odd group of words. The point is that there is a hierarchy of decoding units available at the perceptual level. The reader ranges his attention between these, depending upon the difficulty of the text he is reading.

Will such a hierarchy be found with codes from simple machines? It is commonly assumed not, and experiments for optimizing code output sounds generally seek to make the information per stimulus, thought of as being in isolation, a maximum. The work of Pollack and Ficks and that of Nye (18) can be quoted in this field.

The problem with past coding schemes was that with few exceptions the comprehension of the message, if even considered, was poor (6). This is particularly evidenced in a multimodal coding scheme. In one case (4) the concentration needed to decipher the code was apparently so great that words of more than six letters had to be sent more than two or three times to be recognized. The ". . . reason given by all subjects was that they tended to forget the first letters of the word while receiving the last letters." This lack of comprehension is a problem inherent in multidimensional and multimodal coding schemes, and it probably is a greater problem with the latter. It is hypothesized that the subject's full attention is required to decipher such a complicated code. Not only must he interpret each component of a given stimulus, but also he must combine these components into a single unit of perception. Since his concentration on the decoding is very great, he has relatively fewer faculties left to interpret the perception. A code, whose main component is one dimension--a melody--it is hoped, would solve the problem because less concentration will be needed to decode the signal. A major point in support of a melodic code is the smoothness that can be obtained. Compare, for example, the subjective effect of a series of notes in a melodic phrase with a series of random stimuli impinging on one or more senses. The former is easily remembered and reproducible even if the person involved has a poor sense of pitch. A code based on such a series of smooth-flowing notes--that is, a unidimensional continuous code--has similar attributes. It can be expected to be readily comprehended and learned. Random stimuli form the other extreme. A two-letter phrase, for example, might consist of the following: (a) left ear excited by a tone of 1000 Hz for 50 ms, right middle finger stimulated (or poked); (b) right ear stimulated by a tone of 7000 Hz for 150 ms, left small finger stimulated. Here, no continuous pattern exists. Such a series of arbitrary stimuli, one feels intuitively, would

form a code less amenable to being learned. This kind of discontinuity is what one has in a multidimensional or multimodal code.

The writer is aware of evidence in favor of multidimensional displays. It must be pointed out, though, that in all such cases a discontinuous unidimensional code was the basis of comparison--that is, the optophone. The evidence is not necessarily valid for a continuous, smooth unidimensional code. On the other hand, if used judiciously, discontinuities may be useful. For example, in Spelled Speech (17), there are characteristics of discontinuous coding present that appear to aid the subject to distinguish neighboring letters. Some attributes of discontinuous coding schemes may, applied in a limited way, be useful in the content of a code having high coalescence. One last point: it must be pointed out that although, physically speaking, the code is unidimensional, subjective judgments of letters are based on a quantitizing process. For example, the letter "k" gives rise to a very characteristic upward moving melodic line; the letters "s" and "o" both are distinguished by having stationary melodic lines. The letter "s" has a higher pitch than the letter "o." Other features are described in Table 1.

In order to produce a hierarchy at the word level from groups of sounds (each of which represents a letter), it must be possible somehow to identify the letter from only a part of the code information. One convenient way, where the letters are represented by a frequency-modulated carrier, would be the use of mean pitch. A single letter with an oscillating frequency can be represented by its mean frequency. A string of letters of differing mean values can be identified from each other without noting how the instantaneous frequency varies within each letter. Other letters might be characterized by two frequencies being mean values over two separate parts. It turns out that both classifications can be used in the musical code. At this point, let us assume that each letter is represented by a constant-amplitude square-wave whose frequency alone is varied. The word "that" coded by the musical code is illustrated in Figure 2. It is seen that the instantaneous frequency for the letters varies with time and that the letters occupy 70 percent of the available time. (These letters were generated on the 7090 computer.) The mean frequencies for each letter are shown and they are not significantly different, but subjective impression is that distinct differences are perceived. Two factors were noted. The one was that the initial part of the information is not perceived. Accordingly, we have discounted the presence of point "l" in each of the curves in computing mean values. The other factor was that natural groupings of the sensations did occur that resulted in mean sensations. This was particularly shown with regard to pitch. For the letter "t," for example, one hears a mean frequency corresponding to the points 2, 3, 4, 5, and 6. The mean frequency is 403 Hz. The last point, 7, is

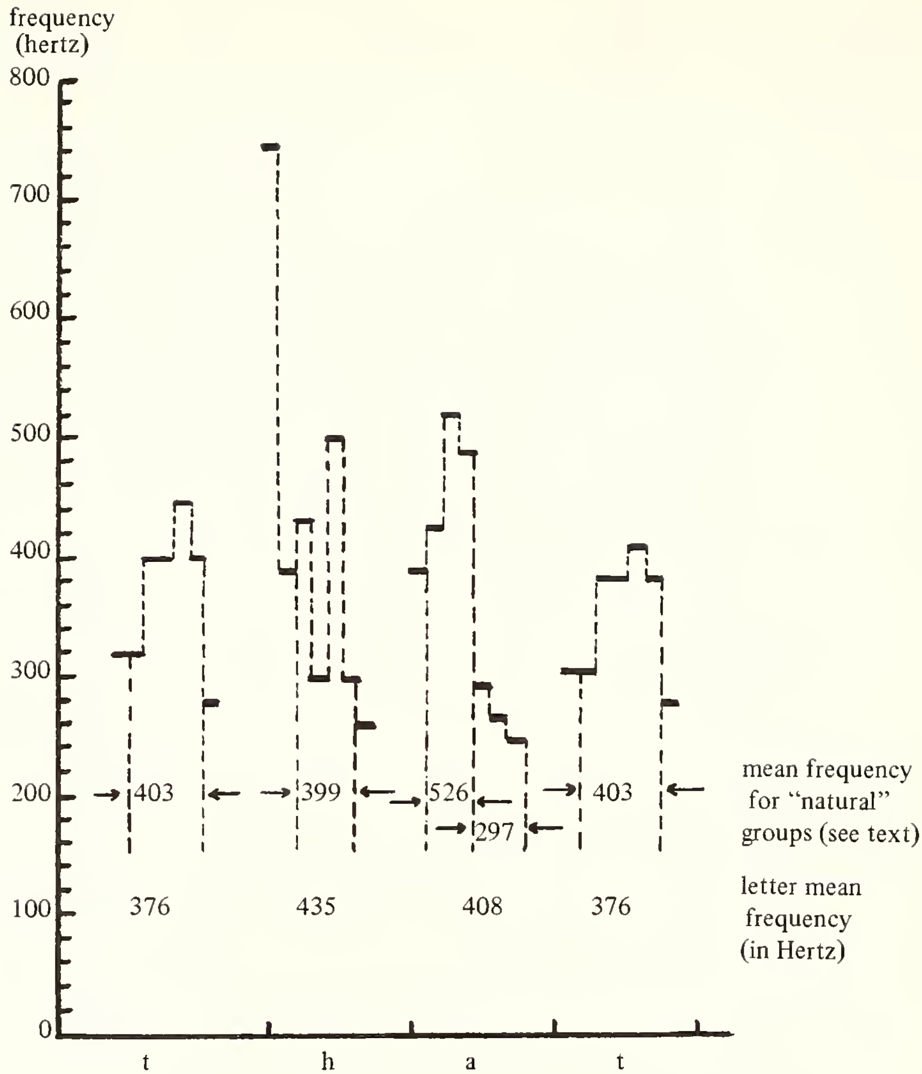

Figure 2. Frequency Modulating Function for the Word "That"

perceived too, and the letter is perceived as a more or less constant frequency terminated by a down-going swoop. (The first point is ignored.) Similar operations are true for the other letters. Omitting, again, the very first point in the letter "h," a constant-frequency tone is perceived, again terminated by a down-going swoop. The mean frequency is rather lower and is 399 Hz. For the letter "a" there are two very obvious sections: a high-frequency one (the first group) with mean frequency 526 Hz; the second is low-frequency, 29 Hz.*

**Subjectively, the tones seemed to vary from "fah" to "doh"--a frequency ratio of 1.37.*

In short, in terms of dominant sounds the word "that" resembles a lopsided mountain that is very distinctive. Corresponding descriptions can be made about other words.

The ability to discriminate a word unit is important if reading is to proceed with any great ease. The tests and training described in the first part of section 3 on a word basis seem to show that subjects can assimilate quite rapidly words encoded in the musical code. One must be free, though, to range between letter units, word units, and (hopefully) sentence units in a single perceptual glance. That is why the training following the word approach reverted to essentially a letter approach in order to develop in the subjects, knowing the alphabet of code sounds, the facility of decoding a word they had never read before. While the author does not claim a special knowledge in the controversial field of teaching reading skills, it would appear to him that a satisfactory training program should aim to develop as many as possible of a hierarchy of decoding skills.

In conclusion, this paper is a description of a research program designed not so much to probe into the question "Why is the optophone a slow and difficult machine to read with?" Rather, we are probing a suggested improvement, the "musical" sound code (section 2). It has desirable qualities of coalescence influencing the predictability of code sounds and a hierarchical set of precepts result. By processing the signals from the slit scanner* in order to omit letter thickness, the output signal is less complex for a given number of optical sensors, and one can take advantage of this to increase the number of optical sensors and improve repeatibility.

In tests three blind subjects were trained for a limited competence in the use of the code. In a total of up to 50 hours for each subject, they had read through the books *I Am Sam* and *The Cat in the Hat,* both by Dr. Seuss. (See section 3.)

2. THE MUSICAL CODE

The machine used in the experiment is shown in Figure 3a. It embodies the features of many simple reading machines, and this is the reason for its relatively massive size. The optophone, for example, can be simulated with this machine by suitable interconnections in the patchboard shown. The Lexiphone, another reading machine, employs the optophone slit scanner but uses a different code: this alternatively can be simulated by the experimental machine. The schematic for the Lexiphone is shown in Figure 3b. From this it will be seen that the machine has a narrow column of photosensitive elements or cells, N_y in number, equally spaced.

**The slit scanner used with the optophone and the Lexiphone is described in section 2.*

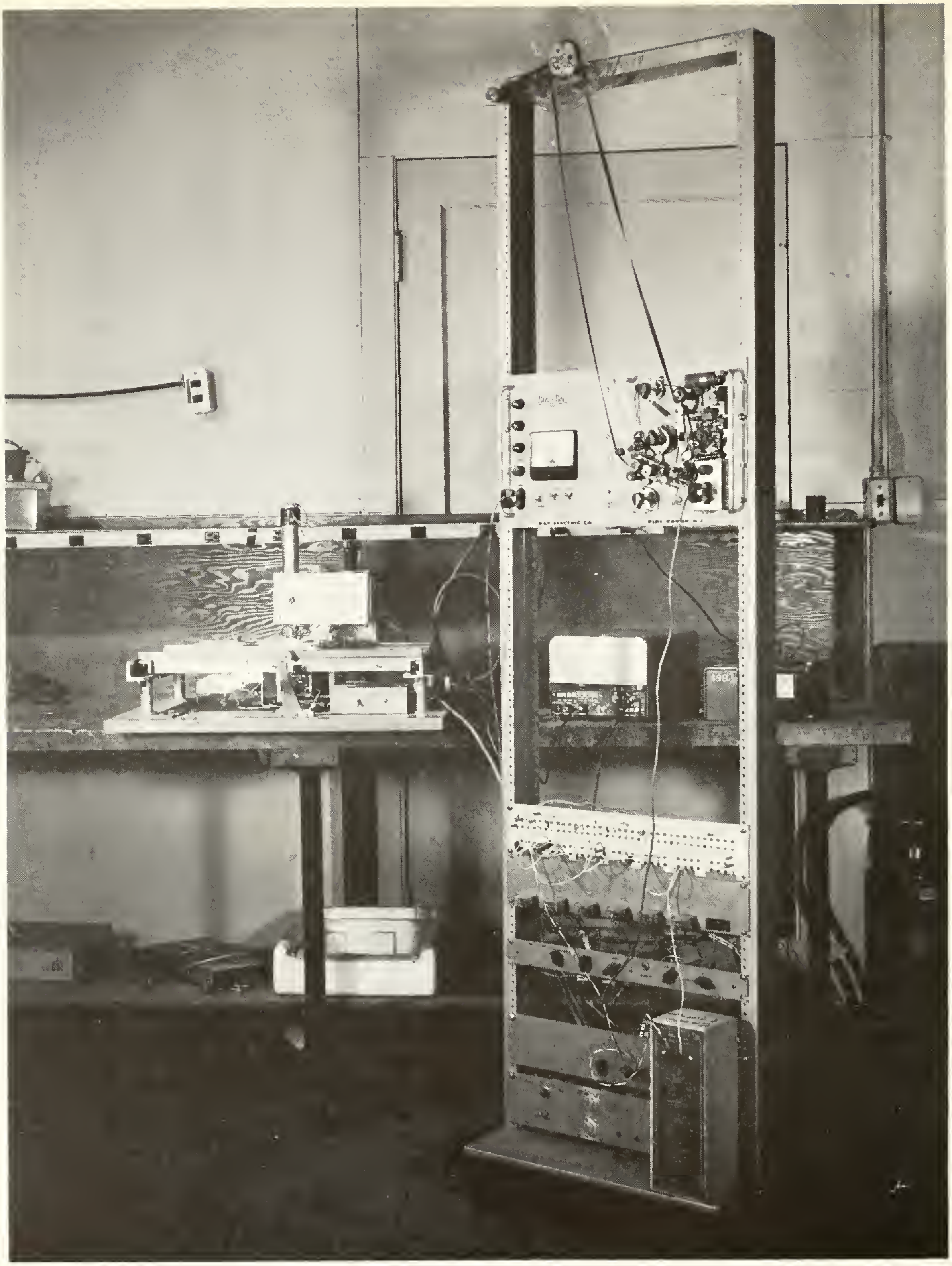

Figure 3a. The Reading Machine: Hardware

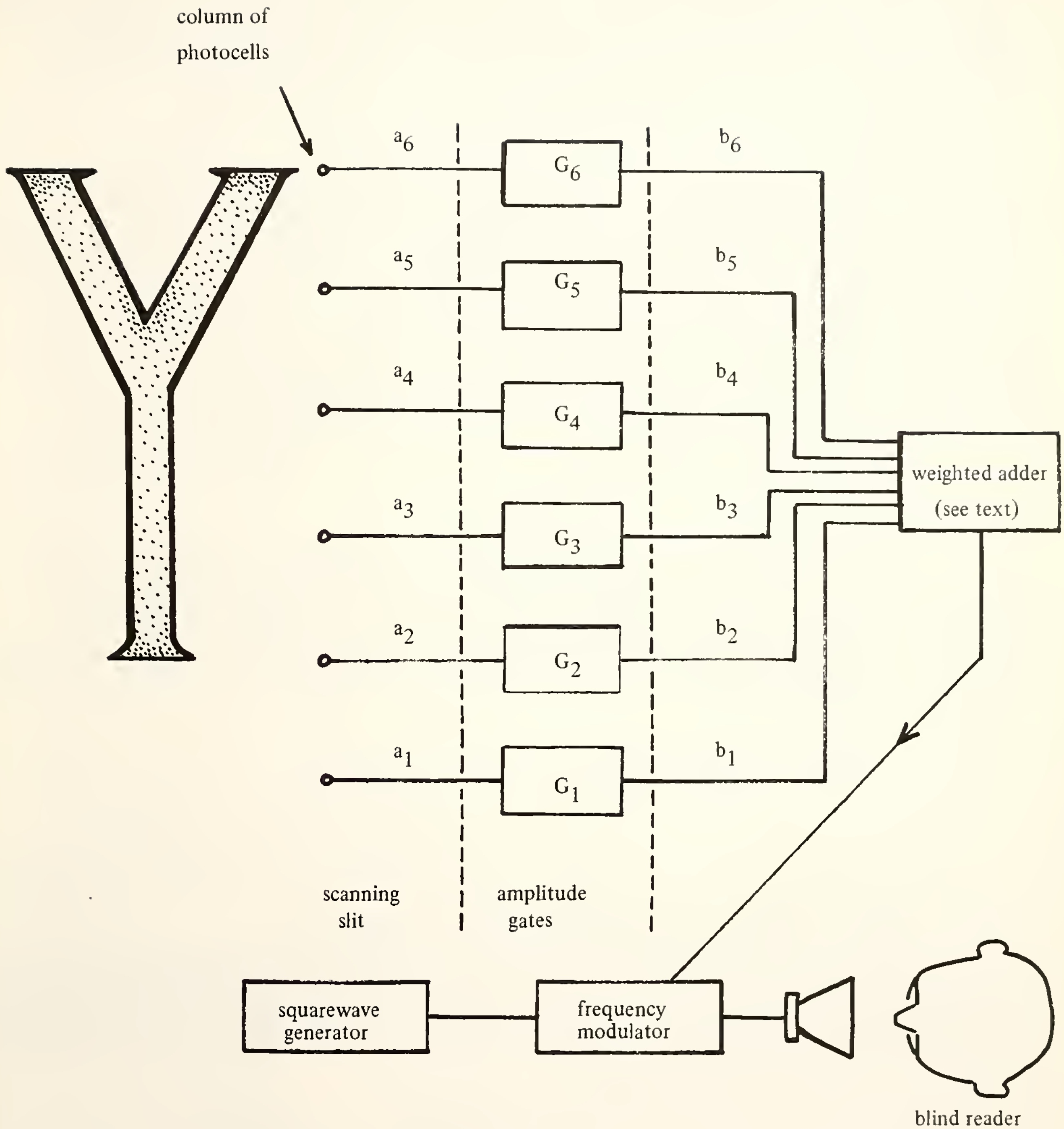

Figure 3b. The Reading Machine: Schematic

The column, referred to as the scanning slit, is held stationary, and the line of print to be read is moved by an electric motor past it. The $a_1 \ldots a_{N_y}$ are voltage levels arising from the black on white print. The voltages will vary continuously from one extreme, corresponding to the cell being completely over black print, to another extreme, when the cell is completely over a white region. Each a is converted by an amplitude gate into a corresponding two-valued function $b_1 \ldots b_{N_y}$ where $b_n = 1$ or 0.

The Optophone Code

The b_n signals of Figure 3b are used in the optophone to key on or off squarewave generators. These differ only in frequency. The outputs from these generators are added linearly and used to drive a loudspeaker or headphones. Each letter produces a melody with accompanying chords, which occur whenever two or more generators are operated simultaneously. The chords occur for a high proportion of the time and must be used to identify the letter. It is the author's belief that people find it difficult to discriminate between chords [this point is supported somewhat by Frank (10) in his work with tonal braille]. The case for the optophone code has been amply discussed and will not be considered further here.

The Melodic Code

The Lexiphone (Mark II) uses the signals from the slit scanner to frequency-modulate a squarewave [a multidimensional alternative designated Mark I is contained in Caple's thesis, (6)]. A first step is to transform the b_n's into a single multilevel signal--equation (1). An alternative form is given in equation (2).

$$f = z = 2^n b_n \qquad (1)$$

$$f = z(x_1, y) = K^{\,y_1(x_1 y) + \sum_{\tau=2}^{m} y_1(x_1 y) - y_\tau(x_1 y)} \qquad (2)$$

The symbols are illustrated in Figure 4.

This f was transformed by scanning along the line of print into a function of time. The transformation was programmed on the TX-O computer at MIT and later, on the 7090 computer at Vancouver. In this way test material used in section 3 is free from avoidable (that is, technological) errors.

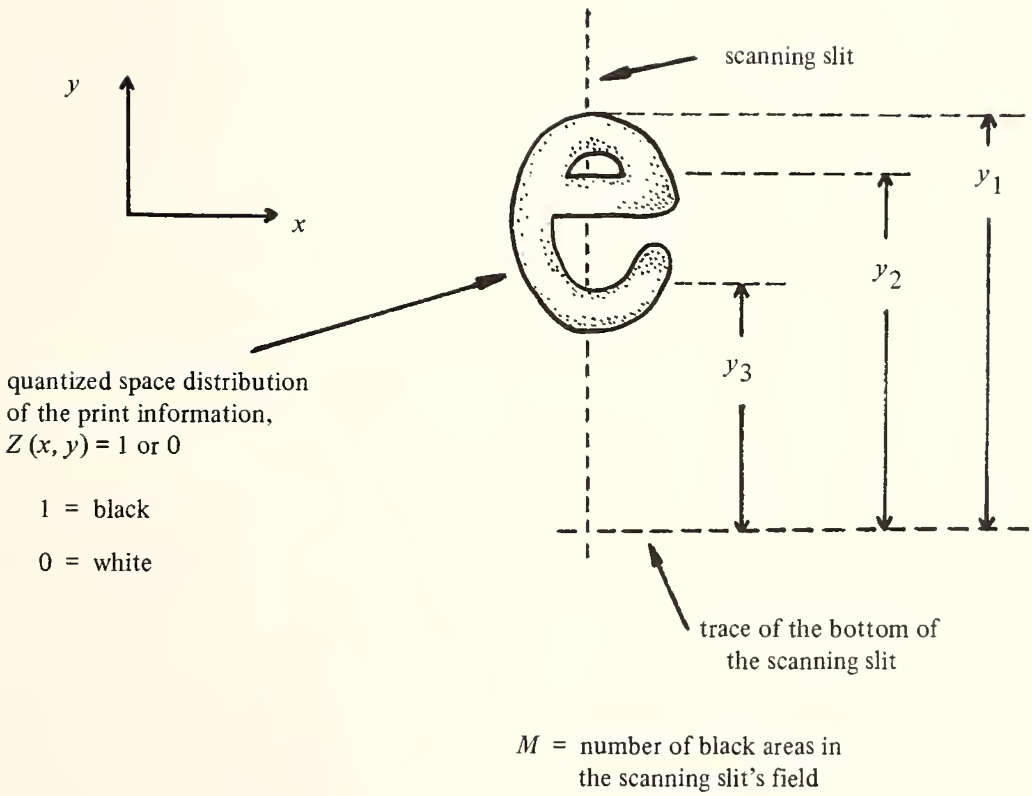

Figure 4. Symbols Used in Equation (2)

The transformation of equation (2) is based on the notion of identifying letters by their upper-lying boundaries only. Information of letter thickness (in this direction) is discarded completely and this operation is largely responsible for a great reduction in the number of levels in the f signal. The factor M in the equation is the number of black islands seen by the scanning slit and has a greatest value of 4 corresponding to the letter g. From this it follows that the number of f levels will at most be $4N_y$ where N_y = the number of photocells = the number of resolvable values of any of the y's in equation (2).

Some ambiguity is left between letters. For example, the letters M and Y produce practically identical f functions. This ambiguity can be removed by specifying another feature of the print letters--an easy one is a "riser" by a characteristic modulation of the code sound. While visually the riser can be thought of as being a vertical black stroke, the machine requires a more precise instruction. Hence, we specify a riser by counting the number of adjacent cells over black. If the number N_b exceeds half the total number, and there is only one cluster of black cells, then a riser is indicated. Using this criterion, the risers in m, n, and I can be obtained, while at the same time the letter E only registers one riser (due to the right-hand vertical stroke).

The riser may be coded by a burst of noise. The riser can also be indicated by amplitude modulation: when the slit is over a riser, the code sound is loud, level 1; over other parts of the letter, the sound is quiet, level 2. Experimentally, 12db difference between the two levels produces a "clear" indication without destroying the coalescent property of the code. Amplitude modulation and noise modulation are both employed.

What are the features in letters that can be identified using the musical code? A basis of argument is to consider z of equation (2)--as it varies as x is varied (that is, as a letter is scanned)--and the information contained in the risers. Letters are made up of straight lines and curves. Most of the straight lines happen to be vertical ones--risers--and these will be clearly indicated by the increased volume in the code sounds. A high-placed and a low-placed riser will be indicated by changes of pitch. The representation of curves is not quite so satisfactory. A commonly occurring z-function will be shaped roughly like the letter n. The closed curve formed by the letter "o," the open curve formed by the letter "c," and more complicated figures such as the letters "a," "e," and "s" produce such z-patterns; parts of such letters as "p" and "b" produce such z-patterns. Discrimination will be affected subjectively by pitch variation mainly. Some close subjective patterns might be expected. Compare o and c. The riser specification separates the two because o has a riser at its left side and its right side, whereas c only has a riser at its left side. It must be noted that the letter "a" has a small vertical portion at its right-hand side. This is classified as a riser.

Another print form giving a characteristic z-function is the periodic form. Periodic or nearly periodic z's are produced by such letters as w, v, W, V, X, x, z. Subjective impression is of a "trill." Another class is produced by essentially a two-valued z-function. Good examples are produced by l, L, and i. Subjectively, a two-note "chord" seems to result. Yet, another class gives rise to an upward-sloping straight-line z-function. The letter "k" is a very good example. A sixth class could be made up from extremes of duration and pitch. For example, the letter "Q" gives the highest pitched sound of any.

Physically, the code can be regarded as a two-dimensional code of pitch and amplitude. Perceptually, the code sounds are very varied. Table 1 contains a list of properties used to identify each of the letters in the lower-case alphabet. Along any one line in the first column are the letters which at first hearing would be easily confused. The identifying feature giving the initial classification is found in column 2. Twelve of the letters in rows 1, 3, and 9 are classified by their mean pitch. The corresponding z-function is n-shaped. The four letters in row 2 give rise to the two-valued z-function. The letters in rows 5 and 7 produce trills that are easily divided by the mean pitch. The single entry letters in rows 4, 6, 8, 10, 11, and 12 are very easily distinguished even on a first hearing. The letter "u" has a low pitch; the letter "m" gives rise to three "thumps" (c.f. the fifth); "y" contains a chord-trill combination; "k" has a characteristic upgoing pitch-slide; "f" is high-pitched and contains a riser; "g" is still higher pitched again with a riser. Residual classification is effected using criteria shown in the remaining columns, and this requires a small amount of training. Perceptually, one uses a large number of dimensions. For example, the melodic line is grouped into five types, loosely five dimensions. Information for the risers listed in column 1 is fairly crude. The riser may or may not be present; it may be high or low placed giving rise to characteristic pitch inflections.

The letters b and p require both sets of information from the riser in order to separate them. This requires a rather subtle judgment. The sound from the p appears to be lower in pitch than the sound from b. The letters l, i, j, t are partly identified through information from the riser shown by the four entries in column 8, row 2. This information takes the form of relative position of the riser and its associated pitch transient. Partly, these letters are identified by their melodic lines.

The property list of Table 1 gives the indication of the discrimination modes that the blind will need to possess in order to use the machine. At most, three properties are needed to identify a letter. For example, the letter b is first classified by its mean pitch into row 3. The riser situated at the beginning then identifies it as either a "b" or a "p," and the subtle difference between the pitch transient of the two risers completes the identification.

Table 1

Property List for Lower Case Letters

No.	Letters	*Main Features*	*Melodic Line* Constant	Mean Pitch	Special	Chord	Trill	*Risers*
1	aes	mean pitch	s	3	es			a
2	lijt	chord		(4)	t	lij		lijt
3	bpdqoc	mean pitch	o	4	c			bpqd
4	u	pitch		6				(u)
5	vw	trill		5			vw	
6	y	trill-chord				y	y	
7	xz	short trill		4			xz	
8	m	risers		(5)				m
9	nhr	pitch		5				nhr
10	k	rising pitch			k			(k)
11	f	high max. pitch		2				f
12	g	high max. pitch		1				g
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)

Note: Entries in parentheses are rarely used in letter identification.

With the pitch dimension we have a six-level scale; with the risers we have to discriminate between at most four letters (column 8). The number of levels in one column is not excessive, and there is an advantage in the use of more than one level in pitch from the point of continuity. If we were to specify the three-letter words "cat," "sat," "the," and "see" in terms of mean pitch only, we could use pitch number associated with column 4 and arrive at the respective code words: 434, 334, 453, 333. This small set is discriminable. More important, the melodies are perceived as single units. With a wider vocabulary, of course, more of the properties in Table 2 than just mean pitch must be used. For example, the sentence "the cat sat on the bat" can be distinguished from "the bat sat on the cat" by the presence of the riser in letter "b." The melodies supplement contextual inference at the word level, and complete identification of all the letters in any one word will rarely be needed. This has been mentioned to the author by subjects learning the code.

Table 2

List of Words Used in First Training Tape

Training VC	*Test CRVC*
i	i
sam	am
am	i am
am	i am
i am	i sam
sam	i am sam
	sam i am

In recapitulation: A musical code that has two features--namely, a melodic line that will be given by equation (2) and a rhythmic quality brought about by accents triggered by risers--has been described. The transformation of equation (2) has two useful properties. One is that vertical alignment of the scanning slit on the line of print is not a critical factor. The other is that by sampling the white-to-black changes of the black print letters information of letter-width is discarded. As this information plays no part in the identification of letters, this operation, it is claimed, will simplify the task of letter identification. In detail, certain characteristic sound patterns can be associated with features in print letters. Six such features are enumerated. Some are better differentiated than others. The letters of the alphabet, both lower case and upper case, can all be identified separately. Table 1 gives the features used to identify the lower-case alphabet. A rough classification by word units can be effected using the six-level pitch variable. This is useful because it leads to word identification without having completely to identify each of the constituent letters.

In the author's opinion the effectiveness of a code is not to be judged on the basis of single-letter tests or indeed by any really short-test procedure. The effectiveness depends upon how readily subjects like to learn it, how easy and how fast they can read with it, and how long it takes to learn. If we take the time that a normal child takes to learn to read visually as a rough guide to learning the code to a good proficiency, very early results are not to be expected but some preliminary results are reported in section 3.

3. FIELD TESTS WITH THE MUSICAL CODE

Experimental material based essentially on a word approach was prepared on a first tape recording from the simulated reading machine--the TX-O computer. Description of the

material in these recordings and a few case studies follows.

The first tape contained a five minute introduction in which explanations were given about the purpose of the reading machine, the nature of the code sounds, and the type of training that would follow. After this, the training sequence proper began; the text was the story *I Am Sam* by Dr. Seuss. Preliminary exposure to the words i, am, sam, and the full-stop was given in a voice-code sequence (VC). One would hear a voice announcing the word I; two seconds later, one could hear the code version of i (lower case letters only were used). A five-second pause followed; then the word Sam would be announced; this would be followed two seconds later by the code version of sam. This sequence was continued through the words listed in Table 2, in the left hand column.

Following this preliminary exposure the subjects were tested for comprehension in a code-response voice code sequence (CRVC). Thus one would hear first the code version of the word i, and in the following five-second pause the subject had to say aloud what the word was. Following this pause a voice would announce the correct response, and this was followed by the code version of the word again. Next, the word "am" was treated in much the same manner and so on through the words in the right hand column of Table 2.

Following this short test the subjects were asked whether they felt they had done reasonably well and were told that, if not, they could repeat listening to the tape from the beginning up to the end of this test. If the subject said he had done well, he was allowed to proceed with further training and testing sequences in the tape. The initial speed was quite slow. In terms of five-letter words, this would be twenty words per minute; but this speed was doubled after the first test. The first test used the words i, am, and sam and the full stop. The second test used these words plus an added four--do, not, like, that.

A variety of subjects have been used with this and later training tapes. The *I Am Sam* training tape was first used with sighted subjects at Nottingham University in England in the summer of 1966. The subjects were sighted psychology undergraduates aged about nineteen and all male. The results of the first four hourly sessions with two subjects are given in Figure 5. Subject S, for example, completed only two tests in his first hour. Scoring was in terms of correct words only. A near miss was given zero credit. In the first test he scored 60 percent and in the test following he scored 20 percent. These two tests with many interruptions and repeats took him a complete hour. This took place in the morning. In the afternoon he took another hour's testing and training. In this he started from the beginning and scored much higher accuracies in the first two tests. Part of this increase is attributable to his remembering the test sequence and part to a greater

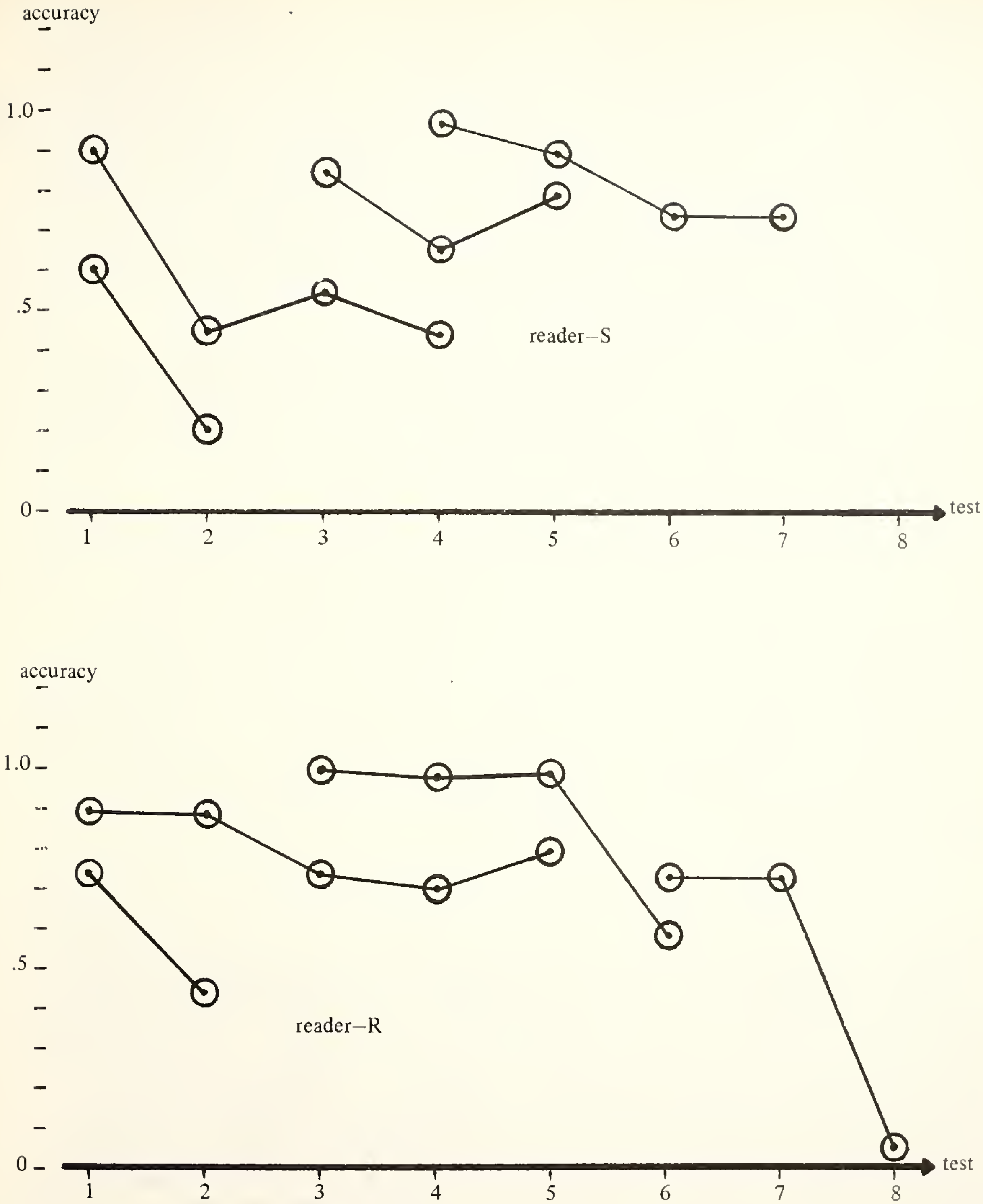

Figure 5. Word Tests Using Form "i am sam" with Sighted Ss

competence in decoding. From either cause, his progress over the same material took much less time (he did not have to repeat material), and his score was higher. In the time saved, he was able to complete two more tests and training sequences in his hour. Toward the end of the hour's work his accuracy fell, probably reflecting fatigue, to around 42 percent. The next day he came in the morning. He did not start at the beginning of the training tape but at the point indicated in the graph. Here again an increase in performance on the repeated material is noted: even at the end of the hour the accuracy is quite high. By this time he was working with a vocabulary of 21 words and the full-stop. In his fourth hour he added another twelve words.

The record for the subject R is slightly better.

A set of tests were done in Boston using three blind subjects recommended by the Perkins School for the Blind in Watertown, Mass. The blind made progress similar to that of the sighted subjects in terms of words added per hour, and a graph showing this progress is given in Figure 6.

For subject D, one can see that after the first hour he knew the code for the words, I, am, and Sam and the full-stop. The subject was teaching himself from the tape and did his studying in blocks of time greater than one hour. The time allocated for the first seven sessions is shown in a table at the side of the figure. After thirteen hours he had completed the *I Am Sam* training tape, and, in doing so, had read through about fifty words ranging in length from one (I) to eight (anywhere). The rate corresponded to forty words a minute. It is misleading to talk of reading. The training was highly repetitive and the context highly illuminating. The training extended over two weeks. Ds performance was typical of the other two blind subjects, and their records are not included.

Next, training with a slightly more advanced text by Dr. Seuss, *The Cat in the Hat*, was commenced. The training format was different. At the beginning of the training tape the complete alphabet in code was given. Lower-case letters only were employed. It was suggested to the subjects that they should be familiar with the sounds through their experience with *I Am Sam*. This seemed to be the case. The subjects were urged to play the alphabet through a number of times starting anywhere to test their ability at recognizing the letters. The subjects spent time doing this before proceeding to listen to text which was presented in a CRVC sequence. One would hear in code the words "the cat in." This was followed by a five-second pause during which the subject had to say what the phrase was. Following the pause a voice was heard giving the phrase, and this was followed by the code version again. At the beginning of the training short phrases with only three letters were employed. These were parts of

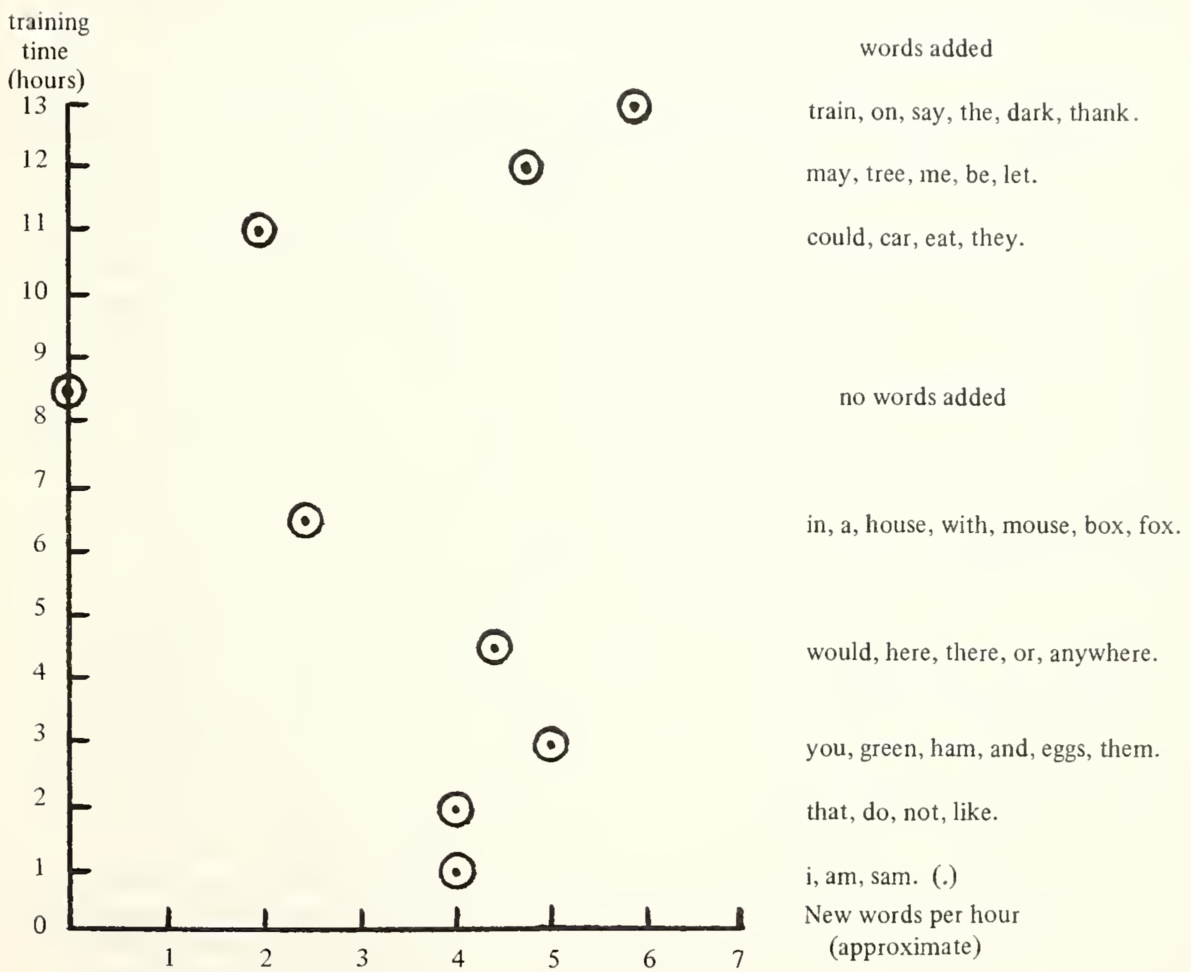

Figure 6. Words Added per Hour Using a Blind Subject in the "i am sam" Training and Testing Program

longer complete sentences. Whenever the phrases belonging to a complete sentence had been responded to, the subject then heard the complete sentence, and he was asked to respond to that. Many new words were added, and the difficulty of the task was proportioned to the subjects' growing ability. Later on, complete sentences, not just short phrases, were given.

After another forty hours' training, subject D had completed the training tape, *The Cat in the Hat*. This has a 260-word vocabulary. His reading rate was at the equivalent of forty words a minute. The other two subjects performed similarly.

Interesting work, which is available in thesis form (13), investigates, for comparison, the problem of recognizing individual letters and groups of letters (without context). In Golden's tests (only salient figures are quoted), single letters from an eight-letter list were presented in a CRVC sequence to sighted subjects of high caliber. The letter duration was 0.25 seconds. It took about three hours to reach a plateau (90 percent recognition). Next, letter pairs were presented in the same format, and recognition of letter pairs again reached a plateau after seven hours. Further tests were taken, increasing the number per group one at a time up to four. A total of fourteen hours was needed to reach a plateau with the last groups. Golden used the encoding of equation (1) [the sounds are similar to those produced by equation (2) under his experimental conditions]. Thus the learning time needed to master a four-letter word was about four times that needed to learn the single letter. By comparison, after 2 1/3 hours D had reached a plateau of assimilation of words taken from a seven-word vocabulary. Contextual inference is high. The time to master a vocabulary of eight letters is of the same order of magnitude as the time taken to master seven words. Assuming that the subjects in all the tests were comparable in ability (reasonable precautions were taken to ensure they were), Golden's longer assimilation time for the four-letter groups is due to three factors: *(1)* the number of four-letter words was 24 against 7; *(2)* there was no context assisting the decoding; *(3)* the subjects were encouraged perhaps the long way round at the decoding of the four-letter words through skills learned earlier. Thus, in a test-training hour session the subjects could listen to any of the previous tapes; they usually chose the preceding one. For example, when being tested on the four-letter sequence, the subjects often listened to three-letter sequences for the initial part of the hour.

Subject D took eleven hours working on a word basis to master the fifty-odd words of *I Am Sam*. Thus working on a word basis, with context, evidently is a more efficient method of assimilating new words than the letter approach. The author must add, with haste, that this is perhaps an unfair comparison to make; both letter-learning and word-learning should proceed in parallel to make a skillful reader.

4. CONCLUSIONS AND DISCUSSIONS

The optophone can inspire tremendous and lasting affection from a very few peculiarly gifted people, but many potential users are discouraged by the slow reading rate ultimately possible. The machine is tricky to set up. It will not hold its adjustment. Adjusting the scanning slit to follow a line of print is practically impossible.

The musical code is an alternative to the optophone chord code. It has desirable coalescent qualities; it also has a discontinuous element represented by amplitude modulation. It has been the experimenter's aim to strike a workable compromise between a coalescence that might be "pleasant" but perfectly meaningless and a discontinuous set of sounds that though emphatically differentiated would be too unpleasant to be listened to for any length of time. Certain characteristic sound patterns can be associated with special features in the print letters. Six such features are enumerated. Some are better differentiated than others. Individually, the letters of the alphabet in lower case and upper case and the numbers can all be separately identified. The problem of reading speed and training time was also investigated. Golden (13) also obtained a base performance for one form of the musical code, indicating that letters can be individually learned.

The reading training and testing of blind subjects (section 3) is not in the end susceptible to a number measure of excellence. The results can be interpreted pretty freely depending on the reader's predilection. The author chooses to regard them as promising. Three blind children could learn to "read" the whole of Dr. Seuss's *I Am Sam* in nine to thirteen hours using word units. Very small groups of words were presented at a time, at a word rate corresponding to forty a minute. Further work with the blind subjects established that *The Cat in the Hat* could be "read" through in a further thirty hours. In the second training a letter approach was used. It is important to emphasize that the reading here is not in the usual sense of abstracting information from the printed word, but that most of the time was taken up in learning how to read. The challenge of the tests increased as the tests progressed in an attempt to match the subjects' developing skills. After forty training hours about 250 words had been read in this fashion. Qualitatively, the author's sighted daughter (grade I) seems to make rather slower progress than this, but we must allow for age difference and other factors.

These experiments by no means close the door on the subject. Many questions remain to be resolved.

1. How critical will the musical code be on the various types of scanner misalignment? It is expected that only fixed amounts of vertical misalignment can be tolerated. Other forms of misalignment will produce distortion in the code

sounds. Whether subjects can read with such distortion present is a critical question to which no answer is at present available.

2. Taken on the whole, is the code sufficiently attractive and the reading sufficiently accurate to be an adequate reward for the blind user? An answer to this important question is unfortunately only available after long-term experiments. Present indications from a handful of subjects who are setting out to learn the code are that the blind are enthusiastic learners.

3. What kind of reading rates can be achieved? This is an important question and the findings described here can only give hope that the rate may be substantial.

4. Can a machine be built with fifty photocells in it? Preliminary plans seem to show no obstacles. The equivalent of about 100 gates (at about 67 cents each) will be needed, and a vacuum deposited column of photocells is being constructed.

5. Will it be possible to guess at a complete sentence fragment by listening only to a single word unit? The experiments have nothing to say on this. The odd word can generally be guessed by listening quite hard to the rest of the text.

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Finally, I thank the blind who have shown their appreciation of the work. Their attitude has been critical. Individuals will disagree with the approach. The subjects, though, are prepared to put a lot of effort into the learning of the code. This has been a constant encouragement.

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THE PHYSICALLY HANDICAPPED IN DENMARK

Editors note: This is a summary of the sixth volume of a report published by the Danish National Institute of Social Research. Summaries of four volumes appear in Research Bulletin 15. *(Copies of tables for this volume will be supplied on request.)*

Abstract

An investigation of some psychological characteristics of the physically handicapped has been performed as part of a greater research program. To get a picture of relevant personality traits, the interviewed persons have been tested with a limited number of questions which indicate dominance of either self-reliance, anxiety, nervousness, depression, aggression, or self-assertion. The study supports the hypothesis that physical disability is compensated for by a relatively high degree of self-reliance, while on the other hand that social and working adjustment are negatively influenced by anxiety and depressive tendencies, even if the physical handicap is rather mild.

Theoretically the study throws light on a general social-psychological theory of deviant behavior, maintaining that socially positive traits will function as compensation for socially negative characteristics and prevent the person from being perceived as socially deviant.

PSYCHOLOGICAL CHARACTERISTICS

During the winter of 1961-62, physically handicapped persons were interviewed in about 10,000 private households representative of the Danish population (9,101 men and 9,490 women aged 15 to 61 years were interviewed, and the number interviewed in the psychological part of the research program was 436 men and 470 women).

Physically handicapped persons are vulnerable to additional strain. But some factors within the persons may help them to compensate for the handicap. Such socially positive factors include good education, high intelligence, or a well-balanced harmonious personality. The purpose of this part of the study is to analyze the correlation between psychological traits and social adjustment which is defined as vocational activity and contact with other people. The investigation does not, however, include psychological testing, and it has, therefore, not been possible to test a general hypothesis about causal relations between psychological traits as primary factors and social adjustment as effect.

Another testing method was incorporated in the interview situation; we sought to divide the interviewed handicapped persons into three groups:

1. Those with socially negative psychological factors, which enlarge the problems of the handicap;

2. Those with no negative factors except the handicap, and
3. Those with socially positive psychological factors, which compensate for the physical handicap.

Individual psychological traits are conceived as behavior patterns and attitudes toward oneself. Socially negative traits are divided into two subgroups: Some people are characterized by anxiety and self-distrust or depressive tendencies and isolation; other people are more aggressive and self-assertive. The positive counterpart is characterized by self-reliance and harmonious personality.

The intelligence of the interviewed persons was estimated by the interviewers, and the results show that the estimation is reasonably good (there is a positive correlation between the estimated intelligence and both amount of work and income). On the basis of information about the individual handicapped persons regarding their physical handicap and their psychological characteristics, it has been possible to analyze how psychological factors sometimes function as compensation for socially negative physical factors and sometimes have the opposite effect, making conditions worse. The fact that a great proportion of physically handicapped persons are vocationally engaged proves that the vulnerability of the physical handicap may be compensated for.

Conditions for the group of handicapped persons must be regarded as a special case of a law of compensatory effects of socially positive characteristics. If a person's social adjustment is threatened by negative traits in personality or in education, he may nevertheless be socially accepted because of positive traits that outweigh the negative ones. A person will often be perceived as quite ordinary and normal, even if he has more or less well-known negatively deviant traits, as he will function adequately according to his total "profile," which involves a number of compensating factors. If he has none of these, his negative deviation will be dominant and make him a deviant person.

The main results regarding the psychological traits of the handicapped are:

1. Self-reliance as a personality trait is rather high for the majority, especially for men.
2. Positive self-expectation is rather good, especially for men. Still, a sizable minority have a small degree: 1/5 of women and 1/6 of men.
3. Negative self-expectation is found in 1/3 of all handicapped, and in 1/10 to a severe degree; but the majority have no negative self-expectation.
4. Severe anxiety and self-distrust is found in 5 percent of the men and 14 percent of the women, and a mild degree of anxiety and self-distrust is found in 22 percent of the men and 34 percent of the women.
5. Nervousness and nervous tiredness is found in 25 percent of the men and 33 percent of the women.
6. Depressive tendencies are found in 9 percent of the men and 12 percent of the women.

The figures seem to be rather high, and even if there is no comparable information about the total population, it is reasonable to say that a relatively great proportion of the physically handicapped are in a psychologically bad position.

Some traits are found only to a limited degree: aggressiveness in 1 to 2 percent; self-assertion in 7 to 9 percent; feeling of isolation in 2 to 5 percent.

The tendency is quite clear; among the handicapped, men are psychologically stronger and more resistant than women.

It is generally believed that each diagnostic group of physically handicapped persons has specific psychological traits, but the investigation has not found any strong confirmation of the hypothesis. So the visually handicapped do not have less self-reliance or more feeling of isolation than the handicapped as a whole, and the hard-of-hearing do not have a higher degree of isolation or aggressiveness, but they have less self-reliance than the average handicapped person. Those with heart diseases have less self-reliance and more anxiety and self-distrust, as was expected. Further, there is a tendency for people with diseases of the central nervous system to be more depressive, and women with an allergy are more nervous.

Many physically handicapped are occupationally engaged, namely 3/4 of the male group and 1/4 of the female group. The amount of *occupational work* is highly correlated with self-reliance and harmonious personality, despite the degree of physical handicap. Self-reliance must be conceived as a basic personality trait developed in the early years of living and, therefore, essentially a basic condition of successful social adjustment.

Correspondingly, it has been found that the chances for occupational work are less the higher the degree of anxiety and self-distrust. This is especially true for men whose sex-role in our society includes expectations of occupational work. Men, therefore, try to overcome the physical handicap and are consequently more vulnerable to psychological traits that counteract the working activities. Among the men who have no self-distrust, there are relatively far more working, even if they are severely physically handicapped. Further, it has been found that depressive tendencies are negatively correlated with amount of work. On the other side, psychological traits such as aggressiveness and self-assertion have only a faint correlation with working adjustment among the handicapped, which may be due to the element of energy in the trait of aggression.

Social contact is defined by fellowship with other people and participation in meetings, and so on. The social contact of men increases with self-reliance. Women's contact with other people is more independent of their personality traits, which may be a general law and not specific for this group. Depressive tendencies are liable to diminish the social contact of both men and women.

Half of both men and women among the handicapped have a relatively limited amount of social contact, which indicates that they

are in a worse position than the total population. In the report No. 25 of The Danish National Institute of Social Research, *Leisure Time Activities in Denmark*, it is found that only 10 percent of the population have a low degree of contact with other people.

Aggressiveness, which was expected to have a negative influence on social adjustment, has proved to be correlated with social contact in such a way that, with increasing aggressiveness, more persons have contact with other people. The explanation may be similar to that formerly mentioned, that the energy, which is inclusive in the aggressiveness, makes the people acceptable in our competitive society. If the other psychological trait, self-assertion, is dominant, however, it has a diminishing effect on the amount of social contact. There may be a general law that self-assertion is rejected, while aggressive energy is accepted. But this is definitely not the case for women, who have the opposite pattern, which may be due to quite different role-expectations.

For this research project an interview technique has been developed which has proved to be an easily used test of personality tendencies or behavior patterns. The test has predictive validity in relation to occupational work and social contact, but most clearly for men, who have the most consistent role-expectations. With a certain probability it is possible to predict the social adjustment according to the answers of the test questions. It may have a great importance for an adequate sorting of handicapped persons who require rehabilitation treatment. Physically handicapped persons are very often able to solve their social and occupational problems, unless they have personality traits that inhibit their motivation and activity. Rehabilitation administration must improve the psychological treatment and the social psychological changing of attitudes. Medical therapy has a fine position and the social-political administration is quickly developing, but it may be insufficient, as a lot of highly qualified expert treatment can be wasted if psychological treatment on a correspondingly high level does not take place simultaneously.

EDUCATION FOR BLIND CHILDREN

F. LeGrande Magleby and Owen W. Farley

Do residential schools do as well as local public or parochial schools in preparing blind students to make satisfactory adjustments as adults? To obtain information that may help answer this question, the writers evaluated data supplied to the University of Utah by the American Foundation for the Blind. The data were obtained through the completion of personal interviews with 784 legally blind adults from Massachusetts, Oregon, Minnesota, North Carolina, South Carolina, and Utah. Ninety-eight of these adults became visually handicapped prior to age three. They are the subjects of this study. Fifty-nine of this group had been educated in residential schools for the blind and 39 had been educated in public or parochial schools. The adult adjustment of these two groups was compared. It was assumed that if significantly more in one group made more satisfactory adjustment as adults, this may reflect a more favorable educational background.

CHARACTERISTICS OF THE GROUPS STUDIED

It is always well to examine some of the similarities and differences in the characteristics of the groups being compared for research purposes. Major differences in characteristics may account for differences in adjustment as adults.

The two groups used in the study were similar in respect to the number of males and females. Fifty-nine percent of those who had attended residential schools and 54 percent of those who had attended public or parochial schools were female. There were even greater similarities in respect to age. The average age of the residential group was thirty-nine years at the time of the research interview, and the average age of the public or parochial school group was forty.

Major differences existed between the two groups in respect to their visual handicaps. More of those in the public or parochial school group had better vision. Ninety-two percent of this group could see light at the time of the research interviews, but only 64 percent of those who had attended residential schools were in this category. Seventy percent of those in the residential school group said they were blind, when interviewed as adults, compared to only 23 percent of the public or parochial school group.

Before presenting the findings, we would like to discuss some of the trends in education for blind children, and some of the positives and negatives in residential or public school education.

TRENDS IN EDUCATION

There is a trend toward sending more blind children to public or parochial schools. In 1952, only 895 blind children were enrolled in nonresidential schools in the United States. Ten years later, enrollment had increased to 9,564. During this period, enrollment of blind children in institutions had also increased, but to a lesser degree--from 5,108 in 1952, to 7,040 in 1962 (1).

In 1963, about 46 percent of the nation's blind children were educated in residential schools and 54 percent in local public and parochial schools, and the total number enrolled in both residential and local community schools was in excess of 17,000 (2).

SHOULD BLIND CHILDREN ATTEND PUBLIC SCHOOLS?

There are several advantages to educating blind children in local public or parochial schools:

1. Most blind children who attend local public or parochial schools live at home, and most of the children who attend residential schools for the blind must be separated from their parents except for visits on weekends, holidays, or vacations.

   It appears obvious that whenever possible, society should provide educational facilities within commuting distance from the child's home. This enables the continuation of close family relationships and the encouragement, guidance, love, and support needed by all children.

2. It costs less to send children to the public schools than to provide for their full-time care, 24 hours a day, seven days a week, in a residential school for the blind.

3. Public schools, by the very nature of their integrated educational programs, teach the blind to compete with, understand, and socialize with those who have minimal physical or mental handicaps.

4. As a general rule, parents of physically handicapped but mentally normal children send them to local public or parochial schools. Many of these children learn to consider themselves "like anyone else" in respect to depending upon their own capabilities and in meeting competition in the world of the nonhandicapped. Shouldn't the visually handicapped have the same opportunity?

POSITIVE FACTORS IN RESIDENTIAL SCHOOL EDUCATION

Residential schools for the blind may be better prepared than most public schools to provide educational programs geared to meet the special needs of the visually handicapped. These students are often placed in ungraded classes under instructors who have completed specialized training courses and are skilled in teaching the blind. As a result, many students who would otherwise fail develop positive self-images and the confidence and the motivation to succeed.

Only a small percentage of our public schools provide ungraded classes for their students who fail. This is evidenced, in part, by the large percentages who become "dropouts." These children, usually characterized by slow reading ability, lack of motivation, and frequent absence from school, number in the hundreds of thousands and, in many areas, may amount to more than one fourth of the children who complete the ninth grade.

THE RESIDENTIAL GROUP DID BETTER

The 59 adults who had attended residential schools for the blind did significantly better (at the 5 percent level of confidence) on six items than those who had attended public or parochial school.

1. Had completed high school (68%--38%)
2. Voted in the last Presidential election (70%--41%)
3. Could read braille (86%--23%)
4. Visited or belonged to a club or organization (80%--44%)
5. Had received vocational training or counseling through public or private agencies (63%--23%)
6. Had friends who lived outside their own neighborhood (48%--28%)

While the following differences were not significant at the 5 percent level of confidence, they are of interest inasmuch as they indicate that in each of the areas under consideration a larger percentage of the 59 persons who had attended residential schools for the blind made more favorable adjustments and also expressed more favorable attitudes in the areas evaluated.

1. Owned their own homes (39%--25%)
2. Were receiving talking books from a circulating library (81%--72%)
3. Were not receiving public financial aid of any kind (58%--40%)
4. Stated they wanted help in finding employment because of their trouble with seeing (42%--29%)

A larger percentage of the public or parochial school group expressed less positive attitudes in five areas under consideration.

On five attitude questions the adult blind were asked to indicate one of six possible responses: (a) strongly agree, (b) moderately agree, (c) undecided, (d) moderately disagree, (e) strongly disagree, or (f) don't understand. The first percentage after the questions that follow refers to the public or parochial school group who checked "strongly agree" or "moderately agree," and the second percentage refers to the residential school group who checked these same items. It is assumed that agreement indicates a negative attitude.

1. It's hardly fair to bring children into the world with the way things look for the future (31%--17%)
2. In spite of what some say, the lot of the average man is getting worse (21%--14%)
3. These days a person doesn't know really whom he can count on (51%--37%)
4. There is little use in writing to public officials because they aren't interested in the problems of the average man (49%--34%)
5. Nowadays a person has to live pretty much for today and let tomorrow take care of itself (46%--38%)

SUMMARY

The writers evaluated adjustments and attitudes of 59 legally blind adults who had attended residential schools for the blind and 39 who had attended local public or parochial schools in an effort to determine which group had made more satisfactory adjustments. At the time of the research interviews more of those who had attended residential schools for the blind were better educated, were more interested in social activities outside their homes, voted in the last presidential election, had received vocational counseling or training, owned their own homes, made more use of libraries for the blind, were not receiving financial aid from a public or private agency, were interested in finding employment, and in some respects seemed to have a more positive outlook upon life.

It appears that residential schools may have several advantages over public or parochial schools in preparing blind children to make satisfactory adjustments as adults. However, this does not mean that the trend toward sending more blind children to public or parochial schools should change. These schools may need to provide more services and give special consideration to the individual needs of blind children, but they need not necessarily reduce the number admitted. Perhaps additional research will indicate that the public and parochial schools of the 1960s are able to compete with residential schools in providing education for blind children.

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A BRAILLE-READING MACHINE*

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Braille is an internationally successful method of reading for the blind. Trained readers find it easy to use, and many consider it more satisfactory than auditory substitutes. However, braille does have some drawbacks: *(1)* publication has, until recently, required the intervention of a human translator; *(2)* the volumes are expensive to produce, ship, and store; and *(3)* each volume is very bulky. The relatively low number of volumes produced and the bulk of each volume account for the high cost and limited use of available braille material.

With modern computers the translation of standard text into higher grades of braille (that is, braille spelled with standardized symbols for groups of letters or whole words) is possible without human intervention other than that needed to prepare the text for the computer (1). The growing use of coded paper tapes in the typesetting used by industrial printers has aided in the preparation of material suitable for computer input.

Problems of cost and bulk remain if computer translation is used only to produce conventional braille sheets with embossed characters. It is not practical for one to acquire a library of these braille volumes, as each volume occupies at least 50 times as much space as its corresponding ink-print volume.

Contemplating the automation of the braille translation process, we have been impressed by the low cost and the compact method of storing the information on magnetic tape. It thus only seems logical to include these features in the publication and storage system of such a process. Therefore, we are led to consider methods for translating the magnetic tape into braille text at the time and place of reading. What is needed for such a procedure is a machine for reading braille text. We present information on the required properties of such a machine (in advance of completion and testing of a prototype) in order to inform others who may be working along similar lines. The utility of such a device seems to justify the technical impropriety.

Three requirements had to be examined before any preliminary design could be attempted. These requirements (reaction of the reader, acceptance by the reader, and speed of presentation) concern the manner in which the raised braille characters are ultimately presented and the speed of such presentation. The first feature to be considered is the reaction of the reader to the replacement of permanent printout with mechanized display. In addition to the obvious desire to discourage the production and

storage of bulky objects, we believed that with little training greater reader comfort would follow the elimination of page handling.

The second requirement, acceptance, is expected to depend on the feature of presentation we have called "mode." Mode concerns the way the raised characters become accessible to the reader and the direction and timing of corresponding movements. We use the term "A mode" to describe presentation of whole lines (with one or several lines at a time available to the reader). In the A mode the upward motion of the text assumes the role of the conventional downward scanning motion of the reader's hands on the braille page. In what we call the "B mode" only a single (essentially endless) line of text is presented, and the line moves sideways, corresponding to scanning a single line by hand movements. In addition to the choice of direction, there is a choice of stepped or continuous presentation of information. In continuous modes (option 1) the flow of reading material proceeds continuously. In stepped modes (option 2) material is rapidly presented to the reader, is permitted to remain available for a period, and is then replaced by new material. The last requirement that had to be determined was speed (characters presented per unit of time).

Modes A and B and options 1 and 2 can be combined to describe four modes. *(1)* Mode A.1 consists of several lines moving continuously upward as the reader scans each line from left to right. *(2)* Mode A.2 is the same as mode A.1 but with the upward motion stepped. *(3)* Mode B.1 consists of a single line flowing past the reader (right to left) while the reader's hands are essentially stationary. *(4)* Mode B.2 is the same as mode B.1 but with sideways motion stepped and the reader scanning each stationary line from left to right. The many possibilities of presentation may be seen in Figure 1.

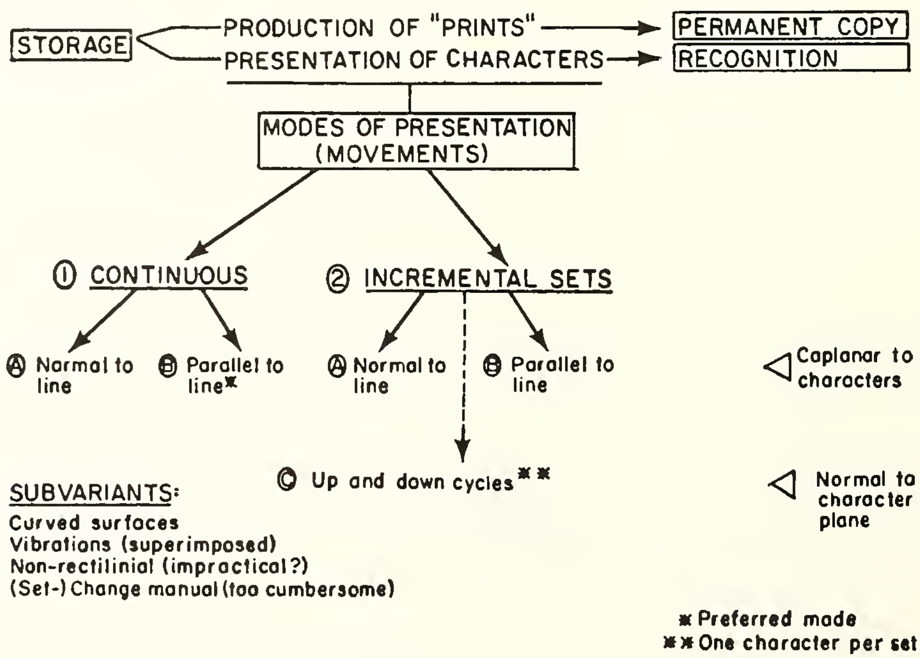

Figure 1. Modes of Presentation of Characters to a Reader

Initial prejudice of the braille readers whom we consulted was for the A.1 mode, which they expected to be most similar to page reading. However, we thought it necessary to get more conclusive evidence, in view of the fact that the B modes (especially the B.1 mode) hold promise for a machine of much less complex design. A testing device was built (Figure 2). This

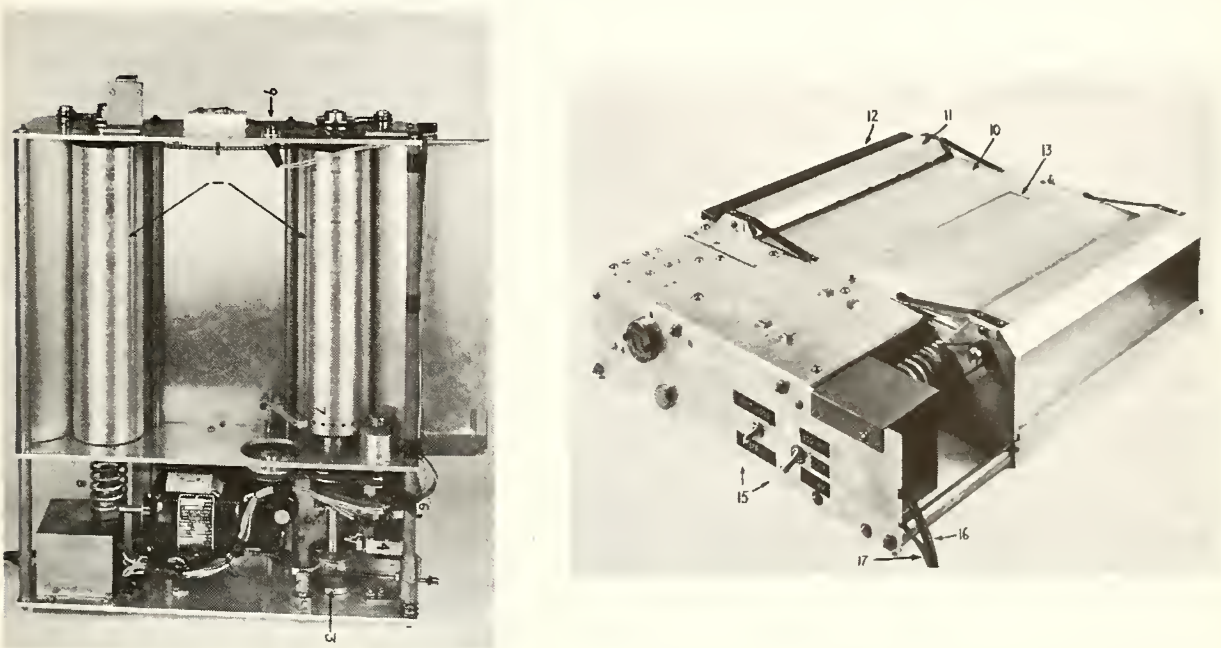

Figure 2. A Braille-Reading Device

(Left) Bottom view with parts labeled. (Right) Top view of the device, reading for loading, with parts labeled. (1) Feed rolls; (2) motor for continuous rotation; (3) unidirectional clutch (for 10-mm steps); (4) solenoid (for 10-mm steps); (5) single-revolution clutch (1 revolution = 230-mm feed); (6) clutch trigger solenoid; (7) escapement (10 mm); (8) brake; (9) socket for (external) adjustable time switch; (10) cover plate; (11) roll guard; (12) paper release bar; (13) cutout (A-mode cutout shown); (14) paper exit chute; (15) mode-selector switches; (16) cable leading to motor speed control unit; (17) power-supply cable.

device consists of two rolls between which a sheet of paper can be fed. Each roll is equipped with two independent drives, one for continuous rotation (adjustable over a wide range of speeds), and the other for achieving feed in steps of either 10 mm (interline braille spacing) or 230 mm (width of a braille page). Two interchangeable cover plates with rectangular cutouts were used; on one the long axis of the cutout was parallel to the direction of travel, and on the other it was normal to it. The paper fed into the machine was embossed with braille characters which were available to the reader within the field defined by the cutouts. Proper selection of drive mechanisms, cover plates, and test sheets of braille enabled us to test read in the four modes described above. For the most part, the reading material used consisted of single words of controlled length (in terms of braille characters per word), arranged in such a way that one word was not related to the next by alliteration, spelling, or similarity of meaning. Empty spaces were left between words on the test sheets. The inclusion of these empty spaces was necessary to permit pronunciation. Rapid speech was still slower than fast braille reading by a factor of two.

These test sheets were presented to readers who pronounced the words aloud as they were presented to them at various rates. Reading speed was defined as the number of characters and blank spaces which the reader could sweep (per minute) while pronouncing 95 percent of the words correctly.

This method of testing was used in preference to subjective testing to avoid having fast readers get the meaning of a sentence by skimming rather than really reading every word, and to eliminate factors such as memory from interfering with the measurement of reading speed. However, such an interpretation of reading rate requires verification. For this purpose three subjects, all fast readers, were asked to read silently (that is, without vocalization or subvocalization) a page of braille (descriptive text from a high-school biology book) as quickly as possible. Their maximum speeds agreed with their maximum speeds in the pronunciation tests. We also used some test sheets which consisted of randomly spaced dots presented in the B.1 mode. The speeds at which the presence or absence of each dot could be recognized were determined. For fast readers the recognition speed corresponded (in terms of finger sweep rate) with the maximum reading speed.

Tests were then performed on ten subjects of both sexes, ranging in age from 12 to 52 years, and varying with respect to years of education received from grade school to Ph.D.; their braille-reading speeds ranged from 60 to more than 300 words per minute. Adjustment to living as handicapped persons was good, and in some cases extraordinary. All readers found the A.1 mode unacceptable. The best readers were ultimately able to cope with it, but found it tiring and unsatisfactory, their speeds having been greatly reduced when compared with other modes. Good readers (200 words per minute) and excellent readers (300 words per

minute) showed consistent reading speeds in all modes but A.1. In the A.2 and B.2 modes there appeared to be about a 10 percent reduction in maximum reading speed as compared with the B.1 mode. Perhaps this is the result of the need to sweep back to the left margin after each line is read. Fair readers (100 to 150 words per minute) and poor readers (less than 100 words per minute) had even more pronounced preference for the B.1 mode than did the superior group, and, in fact, some of them achieved much higher rates with it than they did with the usual braille text.

It thus appears that the B.1 mode, which we had considered desirable for engineering reasons, is preferred by readers. To substantiate our conclusions we asked each reader for comments on the B.1 mode. (Unfortunately, we revealed our prejudices for certain modes.) There was unanimous agreement that it was acceptable, and probably easy to adjust to. Several hoped that use of such a mode would improve their reading speeds (the B.1 mode has some features akin to those that are used in training for speed reading, and many thought that it might improve their reading comfort and enjoyment).

At this point we prepared the following set of criteria for a braille-reading machine. *(1)* The machine should be conveniently portable. This implies at least an optional battery operation and a weight of approximately 4.54 kg. *(2)* The machine should be inexpensive. An estimated production cost of less than $500 should put it within the financial means of professionals. There are approximately 380,000 blind or severely visually handicapped people in the United States. Let us assume that one out of eight in this population reads braille intensively when braille reading material is more widely available. Free distribution of reading machines to those who need them would then entail expenditure of approximately $25 million--not an excessive amount by government or foundation standards. *(3)* The machine should be durable, with simple and convenient controls, and should require standard supplies such as batteries. *(4)* Presentation of material should be in the B.1 mode, and the characters should be erased after they have been read. *(5)* The machine should allow the magnetic tape to move quickly forward and backward, permitting the reader to locate any desired page or passage of text easily. *(6)* The code used on the magnetic tape should be producible as direct computer output. It should include pagination, indexing, and cueing features for the reader. *(7)* The tape (including box and reel) should contain at least 1000 words per cubic centimeter of space it occupies to make the system competitive with ink-print volumes. *(8)* The maximum rate at which the machine presents characters should exceed 22 characters per second. (Three of our subjects routinely achieved this remarkable speed.)

In addition to these requirements, certain accessory features would be highly desirable with regard to the use of the machine for writing and annotating. With the addition of a

device incorporating a braille typewriter keyboard it should be possible to type directly onto magnetic tape. A blind author could then have his text translated into standard print by means of a computer. More commonly, it would simplify his letter writing and note taking, and would also be useful for making annotations in space provided on book tapes. Acoustic recording (perhaps on an extra channel provided in a multichannel book tape) would permit oral annotation. Further features may emerge as development of the machine proceeds.

REFERENCES AND NOTES

1. The American Printing House for the Blind, in cooperation with IBM, has developed a method of translating braille by means of standard punch cards for computer input. The Computer Science Laboratory and Honeywell have developed a similar system. The Mechanical Engineering Department of the Massachusetts Institute of Technology is working on computer translation bypassing the step of the punched card. [See also R. W. Mann, "Enhancing the Availability of Braille," *Proc., Int. Congr. Technol. Blindness*, Vol. 1 (American Foundation for the Blind, New York, 1963).]

2. I thank E. Groh, T. Pienas, B. Burson, P. Grunwald, L. Wos, B. Spinrad, Mrs. Gretel Grunwald, and Mrs. Julian Levi for their valuable support.

THE DESIGN AND USE OF A LIGHT PROBE FOR TEACHING SCIENCE TO BLIND STUDENTS

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The evolution, design, and use of an optical light probe particularly suited to general use in teaching laboratory science to blind students is described. Devices of this type have been frequently conceived, but have not been constructed for versatility and convenience. Their potential use seems to be overlooked, mostly because they are not suitable devices with which to read. The experience in this particular case was in a physics laboratory not otherwise prepared or equipped for blind student participants, and the experience showed that a simple pocket-sized light probe with certain necessary features proved to be the missing link to enable ordinary experiments to be done by the blind.

INTRODUCTION

At the start of the past year [1965], during which time the author was responsible for the general physics laboratory at Princeton University, a student who had been blind since the age of three elected the course. It soon became apparent that he wanted to take the laboratory work in the same form as the other class members. Although his major interest was in paleobotany, it was clear that he had a particular interest in the physics laboratory as a place to learn about measurement. It also became clear at the start that to work in the laboratory with a partner who could see would deprive him of the particular experience and confidence that he needed to obtain.

Since this was an unusual situation at Princeton, no special equipment of any kind was available to aid in teaching the blind. It was not hard to think of a large number of experiments that were very natural to carry out without vision: experiments that involved acoustics and mechanical experiments in which the apparatus and its dynamics could be sensed by touch. Of course, many simple adaptations of existing apparatus were easily made. Some meters could be felt when the glass cover plates were removed; a lecture-style 1/100 second timing clock with the cover removed was available. Apparatus from the general stock with engraved markings could be selected, and all the instruments could quickly be marked in braille by attaching small 50 mesh

polystyrene or Dowex ion-exchange resin beads to a piece of Scotch black electrical tape and taping the pattern to the apparatus.

Nevertheless, it was desired that the student should do many of the same laboratory experiments as the others in the course, not only because the experiments were pedagogically appropriate, but also to give him a sense of common participation. In attempting to do most experiments, some simple snag usually appeared. An etched graduate could be used to measure a quantity of fluid in an experiment which required this knowledge, but how could the fluid level inside be located? An experiment to illustrate the statistics of random counting rate was a part of the laboratory, but how could the blind student see the neon lights of the binary scalar? In some of the experiments requiring the use of a sensitive null galvanometer or mirror galvanometer, how could these be read? Mechanical experiments with a pendulum or gyroscope could easily be comprehended by touch, but how could the motion be felt without perturbing the system to such an extent that interesting but subtle effects would disappear?

It was immediately obvious that all these problems could be solved by a small photoelectric light sensor which could be focused at short object distances as a microscope, at intermediate distances as a "flag" for moving objects, and at infinity for certain optical experiments. It was also obvious that the easiest and most sensitive way to sense the light was to have the photodetector convert the light level to the frequency of an audible tone. A discussion with personnel of the Recording for the Blind, Inc. showed that there was little general knowledge about such devices. A later discussion with personnel at the American Foundation for the Blind revealed that such devices had been previously conceived (1) and that a few had been built and tested (2), but were not available, had not been produced in quantity, and were not listed in the catalogue of Aids and Appliances of the Sales Division of the American Foundation for the Blind. It also became clear that the potential uses had not been properly imagined. One of the primary purposes of this discussion is to suggest that the situation should be changed.

THE LIGHT PROBE

The first model of the light probe was a bakelite model similar to that illustrated in Figure 1. The illustrated version was constructed shortly thereafter, was used throughout the year, and provided the basis of experience which the author and his student accumulated. The electronic circuit is similar to the circuit shown in Figure 4, except for switching details. The light sensitive element is a Clairex CL 603 AL CdS photoresistive cell mounted in the pen-sized aluminum tube at the image plane of a set of interchangeable lenses. The usual method

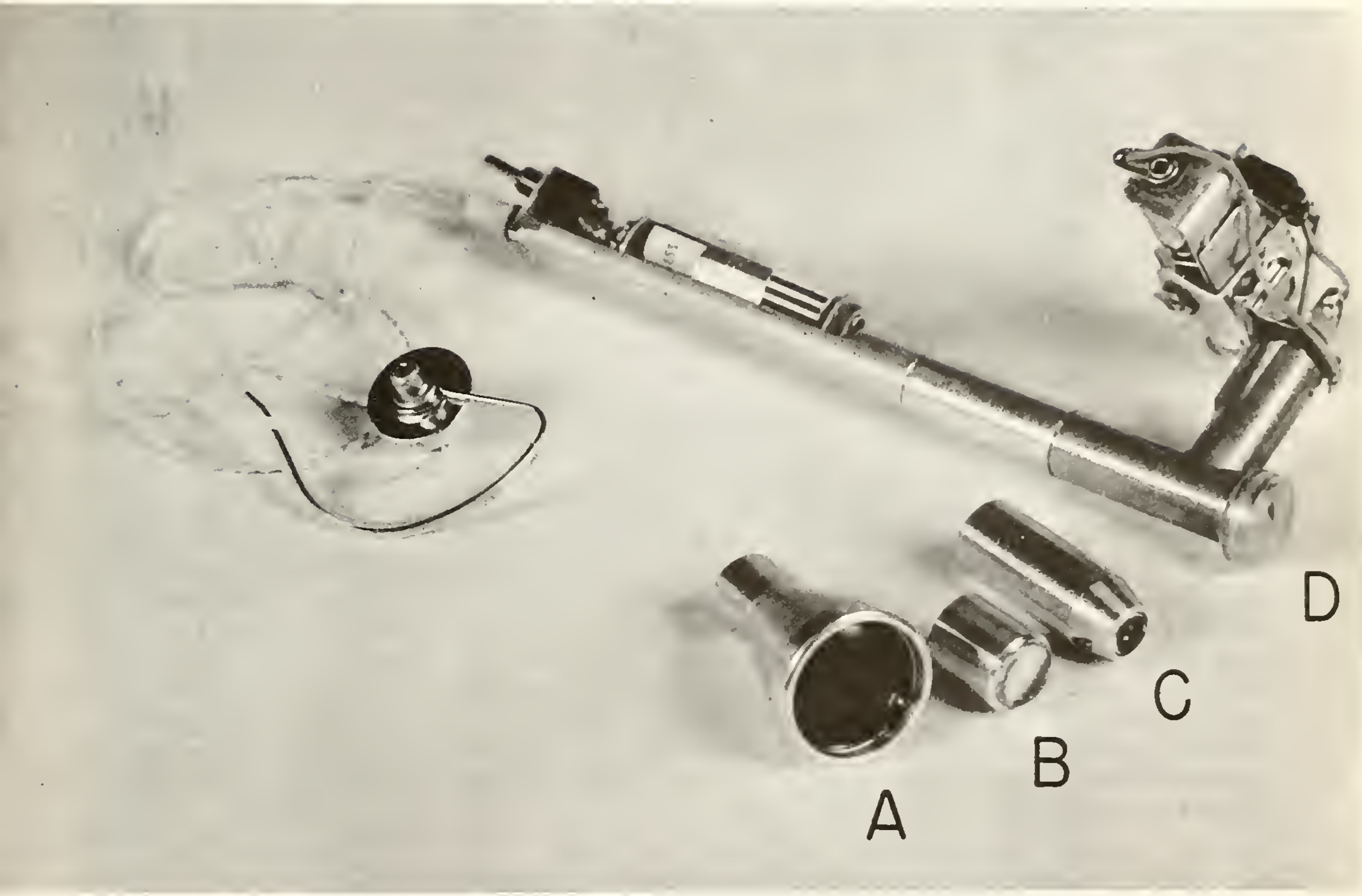

Figure 1. The Light Probe Used in the Laboratory

The interchangeable lenses labeled A, B, C, and D are described in the text.

of using a variable resistance to control the frequency of an audio oscillator is to employ a Wien bridge or RC phase shift or multivibrator circuit, but the working impedance range of the photocell, 50 K to 5 Meg, made reliable oscillation of these types of circuits over a wide range very difficult. Such circuits also necessitated the use of a dual element photocell. It was therefore found more desirable and very much simpler to use a two-transistor RC feedback oscillator in which the photoresistive light cell acts as the bias resistor for the first transistor. The varying base current produces a greater change in the input impedance and gain of the first transistor, and produces stable oscillation with greater "contrast" or change in frequency with light level than does an ordinary RC circuit. The circuit was powered with an AAA battery, and a 90-cent transistor radio earphone was used. The circuit on-off switch was the earphone plug itself, and the miniature switch shown in Figure 1 was a three-position switch to change the frequency of the circuit to compensate for different working levels of illumination.

Different optical functions were performed with the set of four interchangeable lenses which attached by sliding fit to the main tube. Lens A with a focal length of 2 in. had an object distance at infinity, and was useful for general guidance and location functions, and for experiments that required the collection of a collimated beam of light (such as the observation of the fringes in a Michelson interferometer). Lens B of 1/2 in. diameter had an object distance about 6 in. in front of the lens and was useful in timing a moving object passing in front of the lens, as well as reading explanatory diagrams on the blackboard and tracing out wires on the table top. Lens C was a short focal length lens to be used as a 5-power magnifier, which had an object distance only about 3/8 in. from the first surface of the lens. It was used to scan the face of an oscilloscope, to locate fluid level and punched holes in tape or cards, to scan across the surface of a real optical image plane, and to tell whether pilot lights or indicator lights of electronic apparatus were lit. Lens D was identical to C except that it contained a semireflecting beam splitter at 45° between the lens and the photocell in order to provide axial self-illumination from a GE 112 flashlight bulb powered by an AA battery. Figure 2 shows this configuration. This system was useful for reading fluid level in an ordinary thermometer, and was particularly useful in reading meters and sensing the position of pointers.

LABORATORY USAGE OF THE LIGHT PROBE

In a laboratory designed only for the use of blind students, it would be easy to imagine many specially prepared experiments that could be done very successfully. However, this single versatile instrument made it possible for the blind student to take

Figure 2. The Self-Illuminated D Lens System

The lamp, battery, and switch are separate from the oscillator and photocell circuit.

his part in the general laboratory. Needless to say, it was not always possible to predict beforehand which experiments were likely to be enjoyed or successfully carried out. Since most of the experimental equipment could be understood completely by touch, the light probe supplied only some additional information needed to complete the job.

It would sometimes require ten or twenty times longer to make such a measurement than would be required by a person with sight (or by a blind person equipped with a special braille instrument). Nevertheless, the important fact was that the measurement *could* be made in a reasonable length of time, and that it could be made *on* an existing or *available* piece of *apparatus*.

A successful group of experiments were those that employed electrical bridge circuits such as the Wheatstone bridge and the potentiometer. Since these employ null measurements, the quantitative measurements need not be made with meters, and the null measurements were made with the D lens system viewing an ordinary Leeds and Northrup sensitive galvanometer. In this application the light probe is more sensitive than the human eye in detecting the motion away from equilibrium of the galvanometer. The student was particularly pleased to be able to calibrate and use a thermocouple and to make a precise self-consistent set of measurements of electrochemical potentials. When at times the author forgot to mark the polarity of a battery cell or when the student forgot the resistance values of a decade resistance box, the light probe was very useful in reading these simple markings.

An experiment to study coupled harmonic motion was arranged with two pendula tied to a single, somewhat loose coupling thread. The general behavior of this system was easy to feel, and the student was delighted to discover that energy was passed back and forth between the two systems. However, by using the B lens to time the motion he was also able to measure the frequency of the symmetric and antisymmetric modes and to discover that the difference in these frequencies was that of the beat frequency when both modes were excited.

An ordinary lecture model of a gyroscope was used for studies of angular momentum. The dimensions and torques were easy to measure, and the precession frequency could be measured by touch with almost no perturbation. The missing information, which the light probe supplied, was the spin frequency detected by putting a dab of white paint on the gyroscope rotor.

The direction and magnitude of magnetic fields surrounding a bar magnet and a current carrying wire were studied. Although it was possible for the student to determine by touch the direction of an uncovered compass needle, it was somewhat frustrating because oscillations would be so easily set up. It was far more reliable to use the light probe, and it also made possible a determination of the frequency of oscillation of the needle, from which comparative measurements of the magnitude of the field could be made.

Several interesting optical experiments could be carried out with the use of the light probe. The properties of lenses could be measured by making an object out of a wire screen or coarse wire diffraction grating illuminated by a frosted light bulb from behind. The image region could then be scanned by the C lens system and the position of the image accurately determined as that plane in which the lines of the image could be heard to be sharpest. Using cylindrical lens demonstration outfits, ray tracing was also possible using the C lens.

After the student had grasped the structure and function of a Michelson interferometer, he was particularly pleased to be able to use the light probe to hear the interference of light. Since the fringe system in the interferometer appears at infinity, the lens to use in this application was the A lens, and the interferometer had to be adjusted so that only a few fringes at most appeared in the field. With this apparatus and initial assistance in adjusting the interferometer, the student was able to measure the wavelength of the sodium D lines and their separation.

The student had an interest in paleobotany and was interested in the possible use of a microscope. It was found that a 35-mm 300-watt slide projector used as the substage illuminator enabled the microscope to project a real image of the field onto a pane of glass about 14 in. above the eyepiece. The light probe with the C lens was used to scan the field, and the student was able to make out many of the interesting structural details of simple organisms and plants. The sensitivity of the light probe limited this projection microscopy to a maximum magnification of 200 diameters, but it is obvious that a real projection microscope would provide enough light for greater magnification.

The C lens light probe was the best arrangement for scanning the face of an oscilloscope. Such a combination proved to be the most convenient apparatus to use to measure the amplitude and frequency of AC and RF signals. Once the Y gain and time base controls of an oscilloscope had been marked and the interval ratios committed to memory, it proved to be a simple matter to make these measurements. AC bridge and resonance experiments could then be carried out. A less simple and frequently frustrating experience was to interpret nonsinusoidal and transient oscilloscope traces. Despite these difficulties, the student was able to measure RC and R/L time constants rather crudely by exponential decay. The C lens also permitted the measurement of the e/m ratio of electrons by sensing the displacement of the electron beam in an oscilloscope tube when a magnetic field was applied.

The light probe with the D lens proved to be of some use as well in preparing laboratory reports. The student took notes in braille and used a raised line tablet. However, for submitting formal reports which were typewritten, the light probe was particularly useful in drawing graphs. It enabled the student to see the underlying coordinate frame, and helped to indicate where he had finished drawing the previous line. In short, although it was not needed in the report work he did for himself, it proved useful in the work he did for others to see.

A PROTOTYPE ONE-PIECE LIGHT PROBE

Although the probe previously described had great sensitivity and resolution, it became clear that practical improvements could be made in a general device. It was found, for example, that although the different lens systems were necessary, the fact that they were removable also led to the fact that they could be misplaced and lost, and could not be conveniently placed in a pocket. It was found that the battery for self-illumination did not really last a practical length of time. It was found that the cord leading from the probe to the ear made the transfer and storage of the device in a coat or shirt pocket less convenient, and it would also become snarled in other parts of the laboratory apparatus.

To solve these problems the probe shown in Figure 3 was designed. Figure 4 shows the electronic circuit, and Table 1 gives a list of the parts used with an indication of their cost. The probe is designed to have no detachable parts, to contain rechargeable batteries, and to have the loudspeaker contained in the end of the probe so as to eliminate a cord to an earphone. Perhaps of most importance, it is planned to be of a size and structure so that it may be removed from a vest pocket like a large fountain pen and put to instant use.

In order to maintain a constant angular resolution and constant aperture, the lens system consists of a short focal length positive lens (a) and a negative lens (b) adjustable at knob (c), of nearly equal power. When the (b) lens is closest to the photocell, the optical system is a 4-power magnifier with the same function as the previously described C lens, and when it is closest to the (a) lens the focal length of the combination is such as to put the object distance at infinity as with the A lens. Intermediate focal distances are also possible. The photodetector (R1) used is a Clairex CL 904L. To provide efficient axial self-illumination, the beam splitter described previously was rejected in favor of a small L12-30 Kay pinlite, L, whose size is so small that it may be mounted right in back of the (a) lens without significantly reducing the aperture. It is extremely important to blacken all the metal parts in the optical region, and this was efficiently done on the inside of the tube by chasing a fine thread (d) along its length before anodizing the optical tube in flat black. A bakelite tip (e) at the end of the tube acts as a support rest for scanning lines, but can be folded back for other purposes such as meter reading through a glass cover, or for long focal length use.

The electronic circuit shown in Figure 4 is similar to that used in the previously described probe, but includes certain practical improvements. Switch S1 is a modified miniature volume control that combines the functions of the oscillator on-off switch and a tone control to adjust the midfrequency of audio oscillation to the ambient light level that happens to be present

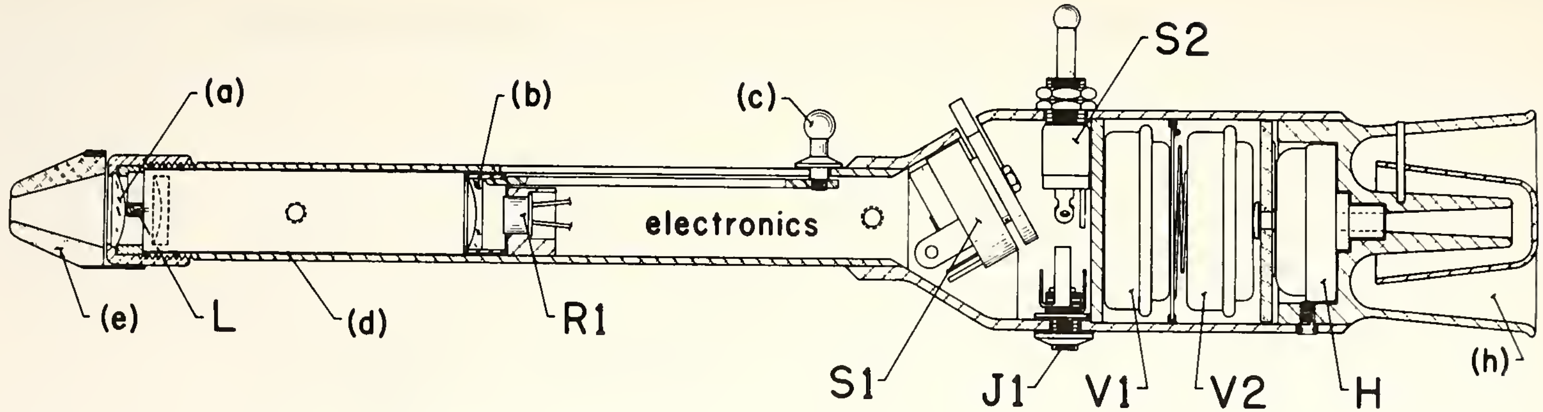

Figure 3. Circuit and Wiring Diagram of the One-Piece Light Probe
Labeled components are described in the text and in Figure 4.

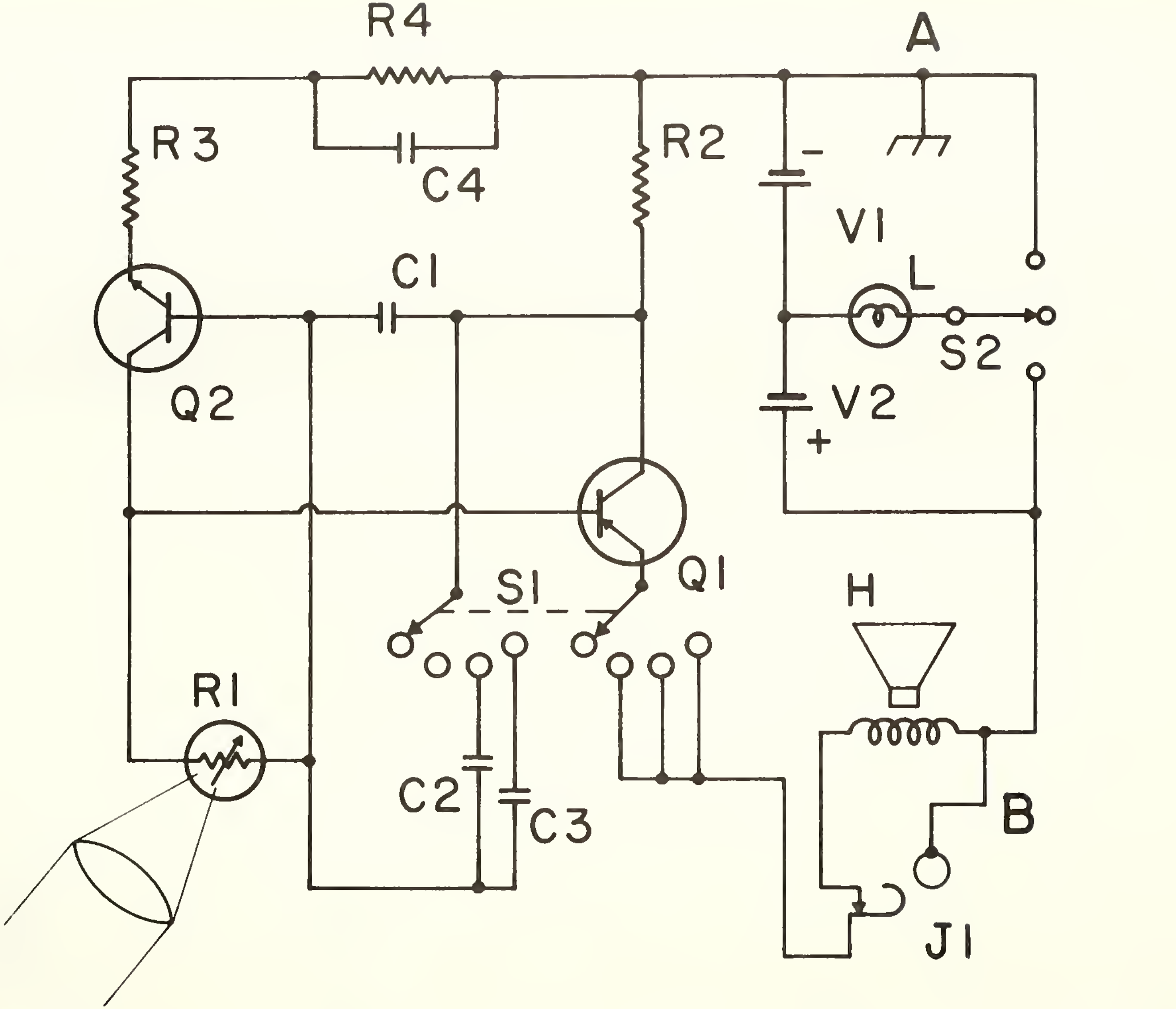

Figure 4. Circuit and Wiring Diagram of the One-Piece Light Probe

Circuit components are described in the text and in Table 1.

Table 1

Electronic and Optical Parts List for the One-Piece Light Probe
(Prices are as of April, 1966.)

R1	Clairex CL 904L	$2.00
(a)	Edmund Scientific 94.005 Plano-convex lens 9 mm x 14.8 fl	.75
(b)	Edmund Scientific 94.564 negative meniscus lens 9 mm x -14.9 fl	.45
H	Fedtro transistor radio earphone (Lafayette Radio)	1.50
Q2 NPN	transistor 2N 706 — Selected from stock for small size, not cost	.90
Q1 PNP	transistor 2N 207	2.25
S2[a]	Miniature SPDT toggle switch (Birnbach 6254)	5.35
L	Pinlite, L12-30, Edmund Scientific Co., 40.690	3.95
S1[b]	Modified transistor radio switch and potentiometer (SK)	.59
	Resistors:	
	R2 150 — 1/4 watt	.07
	R3 620 — 1/4 watt	.07
	R4 16K — 1/4 watt	.07
	Capacitors:	
	C1 500 pfd 6v	.21
	C2 .01 mfd 3v	.25
	C3 1 mfd 6v electrolytic	1.30
	C4 .1 mfd 6v	.78
V1,2	Ni-Cd rechargeable batteries, 225 mah, Burgess 2 CD-4	1.76
J1	Sub-miniature phone jack (Lafayette Radio)	.10
		$22.35

[a]Lamp Switch

[b]On-off and tone level switch

in any particular use. This must include a very wide range; from use outdoors in sunlight to the very low levels needed to see a faint optical image such as that projected by the microscope described in the previous section. Switch S2 is the on-off light switch. Because the oscillator circuit works more reliably on 2.5 to 3 V, but the available pinlites operate on

only 1.25 to 1.5 V, this switch is arranged as shown to connect only one cell to the lamp. This provision also means that there is a "spare" battery for the lamp. With 225 mah cells, V1, V2, this provides about twelve hours of life when the lamp is lit and about five days of life when the lamp is not lit.

As previously stated, the loudspeaker is mounted in the case so that no cord need be attached to the unit. The speaker is a transistor radio earphone (H) with a small exponential horn (h) attached. It is loud enough to be heard across a quiet room, or loud enough to be heard two feet away in an ordinary noisy room. In the event that an earphone is desired, a miniature phone jack (J1) is also provided. It can be seen from the circuit that this phone jack, which is insulated from the case, is also the contact B for recharging the Ni-Cd cells. The other contact A is the grounded case.

CONCLUSIONS AND DISCUSSION

As a consequence of the experience described previously, the author has come to a number of conclusions.

1. A versatile probe of this kind is extremely valuable to both the teacher and the user in science and engineering in circumstances where the laboratory or situation is not routine, and when it is hoped that the user can find his own way.

2. For maximum utility, the probe should be compact and self-contained so that it may be available and used with the same immediate convenience as a fountain pen.

3. Lack of interest in light probes in the past appears to come from the fact that such devices are not useful for reading (3). When one considers the complexity of two- and three-dimensional vision in the eye, it is obvious that a one-dimensional audio trace through the scene is inadequate. Nevertheless, in the abstracted situations that arise in scientific observation and measurement, such an aid is extremely valuable. It is probable that this is because there is already *some prior idea of what to look for*. Under these circumstances lines, points, lights, and light-dark interfaces can be seen and interpreted and thus provide essential information which could be obtained in no other simple way. Another impediment to the interest in such a light probe is the greater amount of attention given to the problem of guidance for the blind. Although this simple device cannot perform the function of range determination, it has been of some use in guidance.

4. A well-engineered light probe should be manufactured in sufficient quantity so that it can be put to use by blind persons and their teachers interested in science and quantitative work. Knowledge of its use and availability should be widely distributed so that it is not necessary for such a device to be "frequently reinvented." Once such a device is in production, blind children who are old enough to make use of simple

tools should be taught how to take advantage of the extra sense, however limited, that the light probe provides.

To the author it seems somewhat anomalous that light probes are not as readily available to the blind as are hearing aids to the deaf, considering that the devices are entirely comparable in expense and complexity. The second light probe described was built primarily to emphasize these points and to determine what some of the problems might be in realizing a small, versatile, and inexpensive device. It is quite obvious that further miniaturization could be carried out, especially with respect to the switches, batteries, and loudspeaker. In fact, the author has already found that a still lower power pinlite may be employed if it is placed just in front of the Clairex photocell instead of behind the plano-convex lens (a), and the use of a lower power lamp then makes possible the use of smaller batteries.

ACKNOWLEDGMENTS

The author is particularly grateful to James G. Smith who developed the audio oscillator circuit that proved so suitable for this application, and who gave so much of his time to the development, miniaturization, and assembly of these devices. The author is grateful to Eric M. Rogers for his general encouragement and his specific advice in the philosophy and method of approach to teaching the laboratory in this circumstance. Especially and finally the author wishes to thank Geerat J. Vermey for his enthusiasm for the laboratory and his patience, good humor, and cheerful interest in the developments that he stimulated and experienced.

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AN ACOUSTIC PATTERN PRESENTATION*

William Lawrence Black

This thesis discusses the design and evaluation of a device for displaying acoustically the motion of a point in a plane.

The input to the display is a pencil-like probe movable on a square writing surface. The output, presented to S *through earphones, sounds like a tone localized in space. The horizontal coordinate of the probe governs the apparent left-right position of the tone and the vertical coordinate governs the pitch of the tone.*

Experiments were designed to investigate S's *ability to follow small motions, to follow fast motions, to make absolute judgments of position, and to read handwritten letters.*

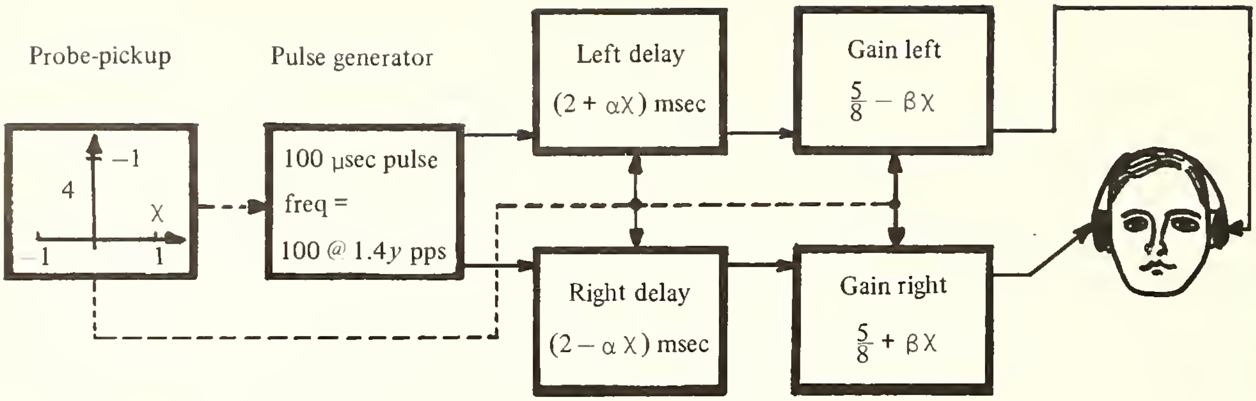
Until the particulars of the various experiments are read, the following list of conclusions should be cautiously interpreted.

1. *The smallest resolvable detail is about one sixteenth the side of the writing area.*
2. *Absolute judgments of position are, at best, accurate to within one-eighth the side of the writing area.*
3. *Motion with "bandwidth" in excess of 3 cps cannot be followed.*
4. *Handwritten letters can be read with high accuracy up to 20 letters/min.*
5. *If only the vertical component of the letters is transmitted, the error rate does not increase much.*

SYSTEM DESIGN

This section describes the development of the display system. Psychophysical data, experimentation, and engineering intuition all helped to shape the final system as diagrammed in Figure 1.

Submitted to the Massachusetts Institute of Technology, Department of Electrical Engineering in August, 1964, in partial fulfillment of the requirement for the degree of Doctor of Science.



Remarks:

Pulse repetition frequency varies from 100 to 400 pps

α is adjustable from 0 to 1

β is adjustable from 0 to $\frac{3}{8}$

Figure 1. System Diagram

The original intent was to simulate the effect of a moving sound source traversing the lines of the pattern displayed. It was hoped that *S* could visualize the pattern by employing his natural ability to localize sound sources in space. *S* could be expected to adapt to such a system with alacrity. However, for reasons given below, this original idea was modified somewhat.

Unfortunately, not enough is known about the mechanism of vertical localization to permit the synthesis of signals giving a strong sensation of vertical displacement. If, as some authorities speculate, the mechanism involves head motion, no such signal synthesis for earphone display is possible (1). Moreover, vertical resolution is, at best, poor.

Instead of horizontal and vertical position, one might attempt to simulate horizontal position and range. Range perception, however, is a complex phenomenon which involves loudness, the ratio of direct signal to reverberations, and the phase difference between pressure and velocity in the incident soundwave (2). Moreover, intensity variations affect apparent horizontal position in a complicated way, leading to nonorthogonal axes (3). For these reasons, range was discarded as a second axis.

I finally decided to use apparent horizontal position for the horizontal coordinate and pitch for the vertical coordinate. At least for an *S* who reads music, the association of pitch with vertical position is natural.

Since broad-spectrum sounds such as noise can be more precisely localized than pure tones (4), the display uses pulse trains with low repetition rates and narrow pulses. Such a "comb" signal has strong harmonics throughout the audible range.

The pitch of the output is varied by varying the pulse repetition rate (but not the pulse width). I designed the electronics so that equal vertical probe motions produce equal changes in pitch along the musical even-tempered scale. The pitch range is two octaves from 100 cps to 400 cps. The choice of 24 semitones was influenced by a desire to keep the vertical and horizontal resolutions approximately equal (5). At frequencies lower than 100 cps it is difficult to follow fast motions (6).

In order to take advantage of both of the mechanisms which human beings use for localization, the display employs both delay and amplitude modulation of the two phone signals (7).

For pure tones of equal amplitude, relative delay produces a nearly linear change in angular position until the delay reaches the Hornbostel-Wertheimer constant k. For larger delays the apparent source continues moving around the head, but also moves away as shown in Figure 2. Delays in excess of $2k$ give the effect of two sources, one in each ear. The constant k depends on loudness and varies from subject to subject, but it is usually between 1/2 and 1 msec (8). Although these data were obtained with pure tones, I thought it reasonable to assume that the effects of delay on pulse trains would be similar. Thus I made the relative delay of the pulse trains to the two ears vary linearly with probe horizontal position. The maximum delay is 2 msec (9).

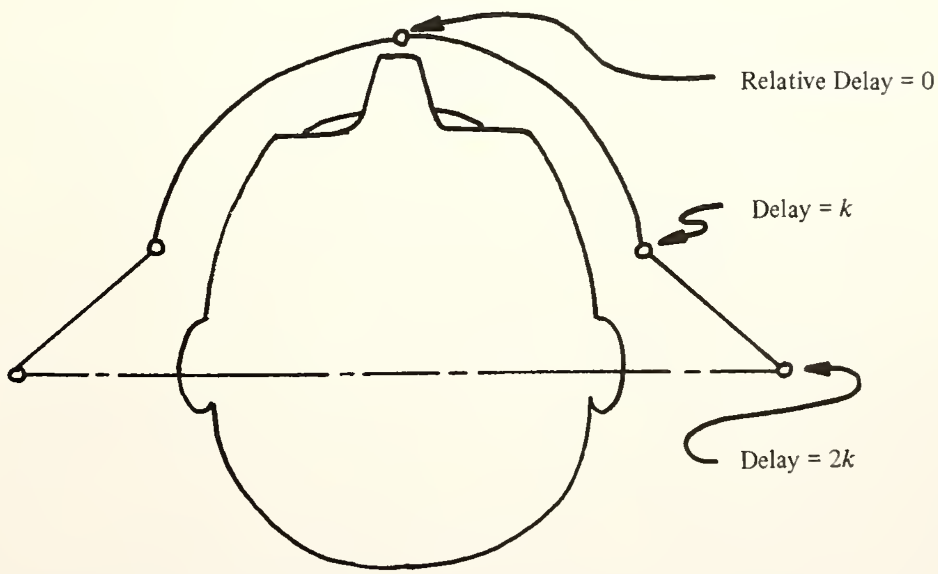


Figure 2. Position of Tone As a Function of Delay

Not much is known about the effect of relative amplitude variations on the apparent position of complex sounds. However, measurements in the meatus show that relative intensities for real sound sources at various angles and frequencies don't exceed 10 or 15 db. The display produces a current ratio of 4 (or an intensity ratio of 12 db) when the probe is in an extreme horizontal position. As can be seen in Figure 1, the amplitude of the output pulse train is linear with horizontal position. Although this produces an apparent dip in loudness in the center, it was chosen for convenience of instrumentation and for lack of any better alternatives.

The earphones are enclosed in baffles that keep external noise from disturbing *S*.

After deciding on the system, I designed and built the final display. Details of construction and circuitry are shown in the Appendix.

EXPERIMENTATION

I spent about two weeks familiarizing myself with the newly-built equipment. Although this preliminary experimentation was informal, it did produce useful information. It showed that the system, as conceived, had no obvious aberrations and that *S*s performance with the display at various tasks was good enough to justify further experimentation.

The first formal experiment was designed to investigate the *S*'s ability to make absolute judgments of horizontal position. I hoped that it would also show whether pitch variation affects the apparent horizontal position of the sound source. If the horizontal and vertical axes were truly subjectively orthogonal, there would be no interaction.

The single *S* was given an audiometer test to verify that his hearing was normal (10). He was then positioned so that he could not see the display. The volume was adjusted to what the *S* indicated was a comfortable level and the chassis pots were switched on in place of the pickup pots. Motion of the probe was simulated by setting the calibrated chassis pots directly.

The experiment then progressed as follows. The pitch was set to 200 pulses per second (pps), the horizontal pot was swept several times back and forth across its entire range, and *S* was requested to note when the apparent source crossed the median plane of his head. The horizontal pot was then moved a random distance off center, and *S* directed the experimenter to adjust it until the apparent source was once again on the median plane. Eight trials were made--four coming in from each side--in the pattern RLLR LRRL. The pitch was then changed to 100 pps, and again *S* tried eight times to direct the horizontal adjustment back to the same point. This sequence was repeated for 400 pps. All of the above was repeated for two more anatomic horizontal coordinates--midleft and midright. Thus there were eight attempts

to reset the horizontal to each of three positions at each of three vertical or pitch settings.

The results of this experiment are shown in Figure 3. As expected, the ranges for the midleft and the midright settings exceed those for the center settings (11). Moreover, the ranges are disturbingly large (12), indicating that judgments of absolute horizontal position are not very precise. The data are inconclusive as to whether pitch variation affects apparent horizontal position. It is certainly possible to draw vertical lines through the ranges corresponding to the anatomic horizontal coordinate. Although it is not apparent in Figure 3, it was evident during the experiment that much of the range was due to *S*'s tendency to forget the point he had in mind and to select a new one (13).

The next experiment tested S'*s* ability to make judgments of relative position and/or velocity.

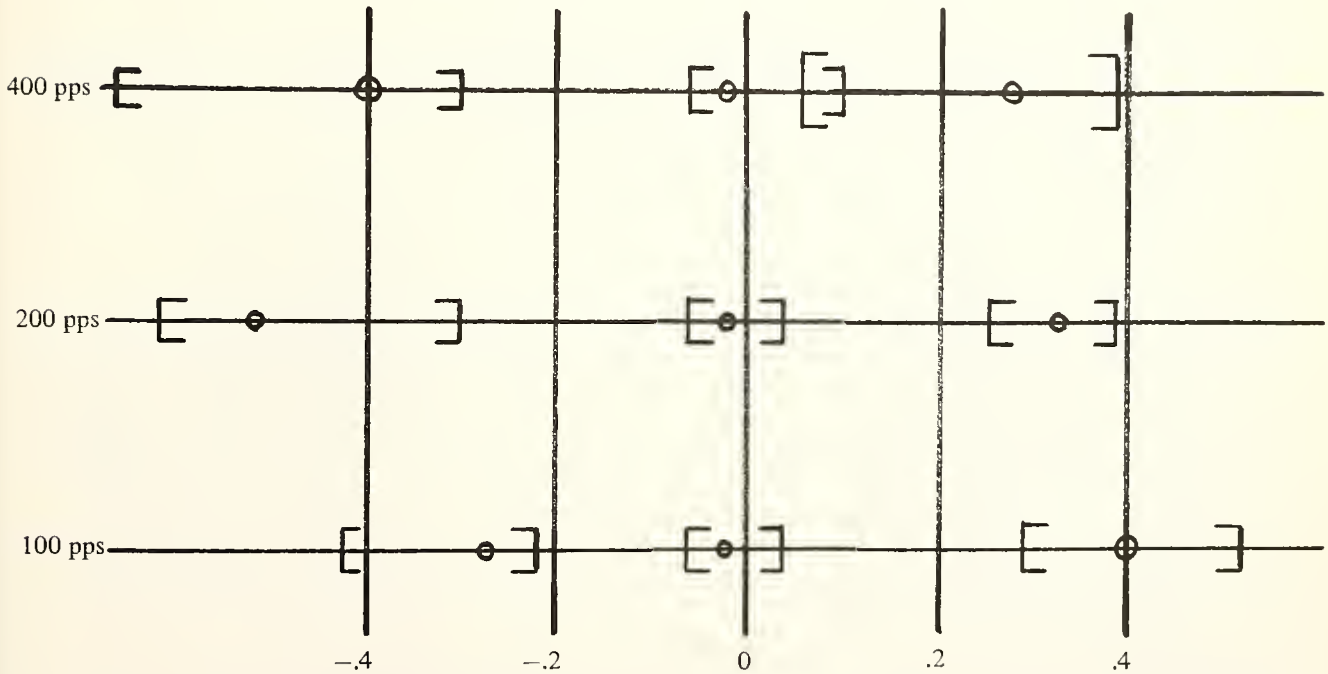


Figure 3. Data Display

(The circles show mean settings; the brackets show the range.)

Each *S* (there were three) had normal hearing. During the experiment *S* was seated so that he could not see the input board. He was given a copy of a test grid (as shown in Figures 4, 5, 6, and 7) and a pencil. An identical grid was attached to the writing surface. The experimenter placed the probe at a node on the grid, announcing the position as he did so. *S* placed his pencil at the same point on his grid. The experimenter then moved the probe at various speeds from node to adjoining node in a random fashion. *S* attempted to follow the motion on his grid. As soon as *S* erred he was corrected, so that he was always sure of his starting node.

Performance at this "following" task was so good that all three *S*s quickly progressed from the coarse grid of Figure 4 to the fine grid of Figure 7. As expected, *S*s had no difficulty sensing the presence and direction of the vertical component of the motion. At first *S*s ignored the horizontal component of motion whenever the experimenter moved the probe along a diagonal line (14), but this was quickly overcome.

Throughout, vertical motion tended to hide simultaneous horizontal motion at the vertical edges of the grids. Performance on the finest grid was substantially perfect except for the brief (15-min.) "warm-up" periods at the start of each session. Grid testing was mixed with other experiments, so I can only estimate the time it took for the subjects to acquire proficiency with the small grid. For all three *S*s it took about five hours to go through the series of grids. Perhaps the learning time would have been shorter if we had begun with the fine grid.

The following experiment was intended to determine how fast a motion *S* could follow.

S (four were used for this part) was seated so that he could not see the input apparatus. A circle template was attached to the writing surface of the equipment with the center of one of the circles at the center of the writing surface. The display was switched off. The experimenter began tracing around the circle (trying to maintain a uniform speed) and, at a random moment, switched the display on. *S* was asked whether the probe motion was clockwise or counterclockwise. The motion was continued until he responded. If his response was wrong, he was corrected. In any event, the display was turned off in preparation for the next circle. Clockwise and counterclockwise drawings were presented randomly.

The results of this experiment were surprising. At low speeds (0.5 cps) all *S*s could follow the motion of the point perfectly. At higher speeds (1 cps) all *S*s throught that they could follow the motion, but their responses were no better than random. I finally concluded that the *S*s were probably ignoring the horizontal motion and concentrating on the pitch. Note that the same pitch signal is generated by circular motion of either sense. Thus, I suggested that *S* actually follow the motion of the circle with a pencil--reserving judgment until he thought that he was in step with the instantaneous motion of the probe.

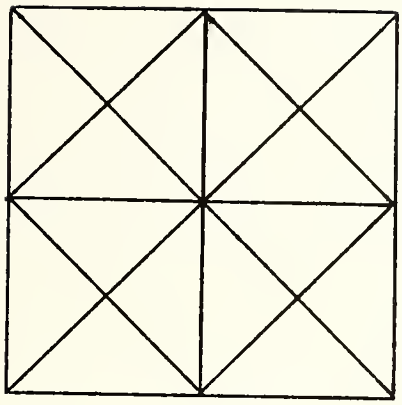


Figure 4.

Coarse Test Grid

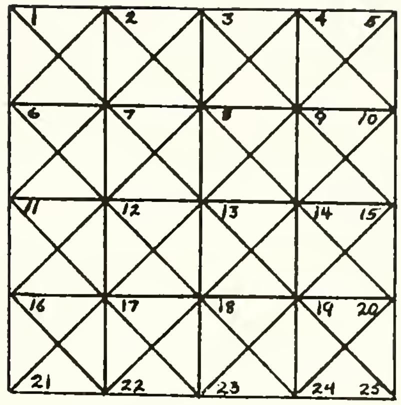


Figure 5.

Finer Test Grid

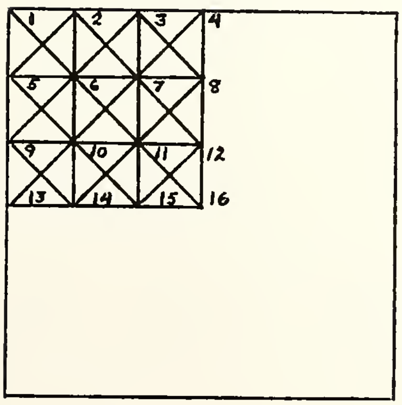


Figure 6.

16-Point Corner Test Grid

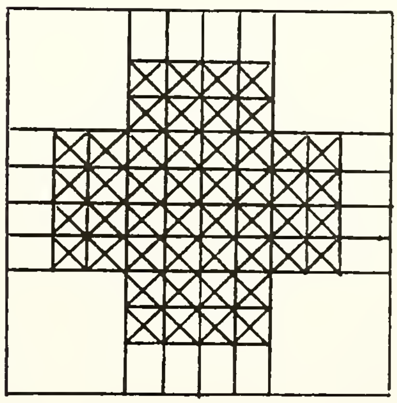


Figure 7.

Test Grid Emphasizing Handwriting Area

This expedient eliminated the false responses at 1 cps. All *S*s lost the ability to follow the motion at approximately 3 cps. This cutoff frequency did not vary for any of the circle sizes used (diameters one half to one eighth the edge of the writing surface), which suggests that the notion of bandwidth is appropriate.

It should be remarked that correct identification of sense of rotation was possible at speeds up to 3.75 cps. However, at these higher rates, the *S*s stopped trying to follow the entire trajectory of the point and employed other strategies. The most successful strategy was to concentrate on the intervals between the two loudness maxima per cycle. The point was going clockwise if the maximum in the left ear came at the beginning of the short interval. The success of this strategy probably depends on the increase in loudness with pitch inherent in the system (15) and the "hole-in-the-center" previously mentioned in conjunction with the amplitude modulation. For trials at these high speeds the circle drawing was motorized to insure uniformity and only one size circle was used.

Resolution at various points on the writing surface was the subject for the next experiment.

Each *S* (there were three) was seated so that he could not see the input apparatus. The experimenter placed a circle template on the writing surface, set the probe to one of the four extremes of the circle ("north," "east," "south," "west"), and told *S* which of the four points was selected. The experimenter then moved the probe along the circle to one of the two neighboring points and asked *S* to identify the new point. When *S* erred, he was corrected. In any event, the next point displayed would be one of the two adjoining the last point displayed.

It was found that *S* had appreciably more difficulty at the left and right edges than at the center, and that almost all errors occurred when the previous point displayed was "north" or "south." With practice, however, all *S*s performed perfectly with circles having a diameter one twentieth the side of the writing surface (except for one subject who had difficulty in the lowest twentieth of the writing area). Because of equipment limitations it was impractical to study smaller circles. This experiment made it clear, however, that the resolution was adequate for handwriting.

The following experiment indicated several things to expect in later experiments with letters.

S was seated as usual and the grid shown in Figure 8 was attached to the input board. Then the experimenter traced along one of the five lines joining the two nodes. *S* (there were three) was asked to guess which line was traversed.

As long as all of the lines were traversed in the same direction, *S*s had no difficulty distinguishing among the paths. If directions were mixed, however, performance degenerated. The lines most frequently confused with one another were lines 2, 3, and 4. Surprisingly, the original level of performance on unidirectional traces was not recoverable during the same session.

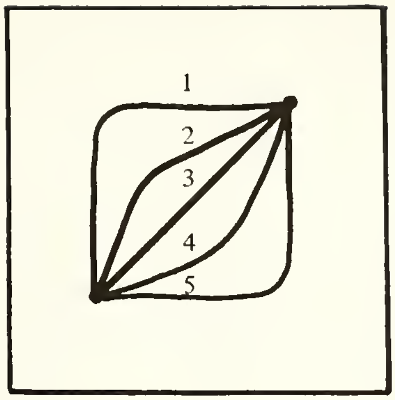


Figure 8. Concave-Convex Grid

S's failure to perform well on a task that originally presented little difficulty can perhaps be traced to fatigue. The performance of one *S*, who was given unidirectional traces only, degenerated to near randomness after about twenty minutes. All *S*s claimed that the task was extremely arduous.

As we shall see later, the inability to distinguish concave from convex causes difficulty in letter recognition.

The next experiment provided more quantitative data on judgments of relative position.

For this experiment an electronic switch was built that switched the equipment from chassis pots to pickup pots for 2.5 sec and then returned control to the chassis pots. This operation was controlled manually by pusing a button.

The single *S* was seated as usual and given a chart identical to that shown in Figure 9. A similar, but smaller, chart (distance between nodes = one nineteenth the side of the writing surface) was attached to the writing surface of the equipment with F6 at the center of the writing area. Thus the lattice on the input table covered the central quarter of the writing area. The probe was set to F6 and the chassis pots were adjusted so that there was no change in output when the button was pushed. The experimenter then placed the probe on the desired node and pushed the button. To the *S*, the probe appeared to sit at F6 until the button was pushed--at which time it instantaneously jumped to a new position. After 2.5 sec it returned to F6.

The steps in this experiment were as follows. The experimenter placed the probe at a random point and pushed the button. *S* pointed to the position on his chart to which he thought the probe jumped. The experimenter then announced the correct position and *S* moved his finger to this position, if necessary, thereby providing some measure of motor feedback.

The actual data-taking was preceded by a half-hour of practice on this task. During the trials each of the 121 points on the chart was presented ten times in random order. The results of this experiment are shown in Figures 10 and 11.

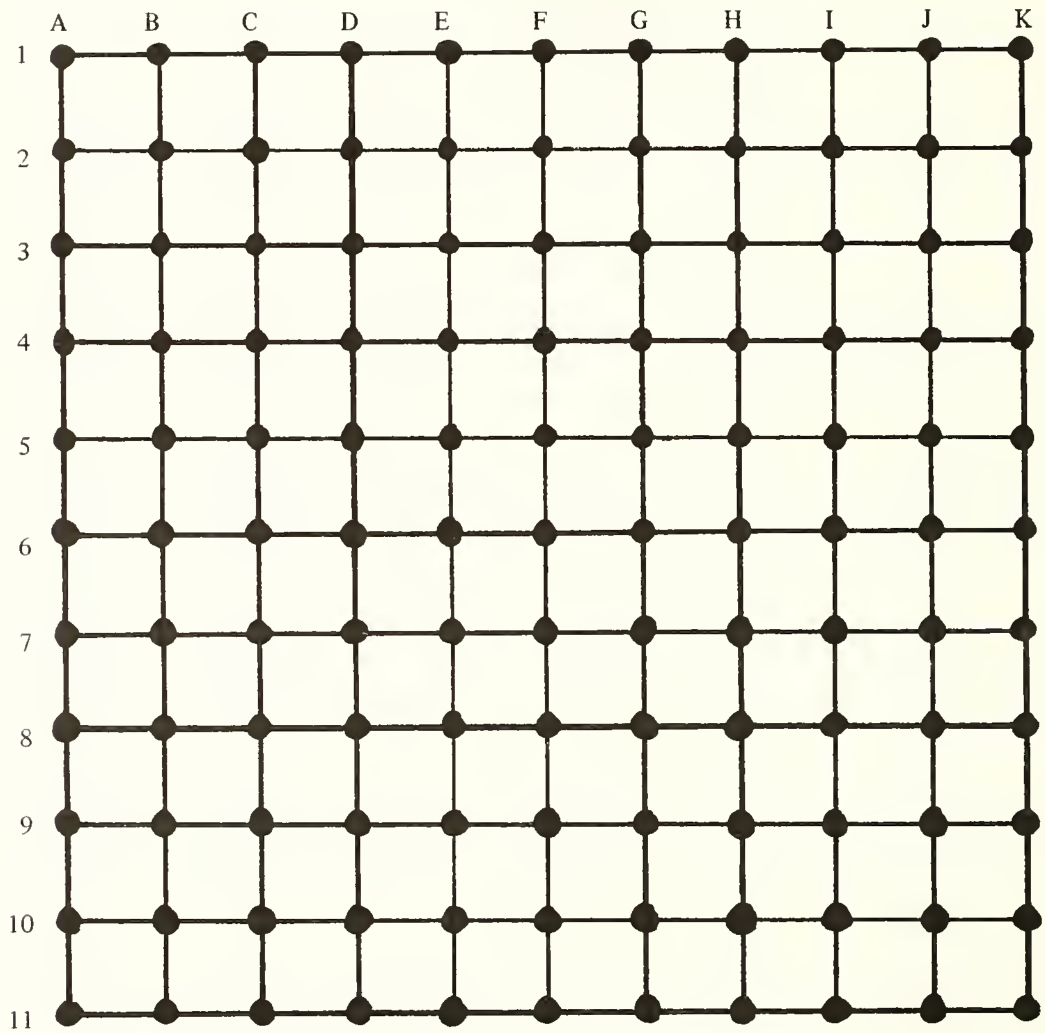


Figure 9. Test Grid

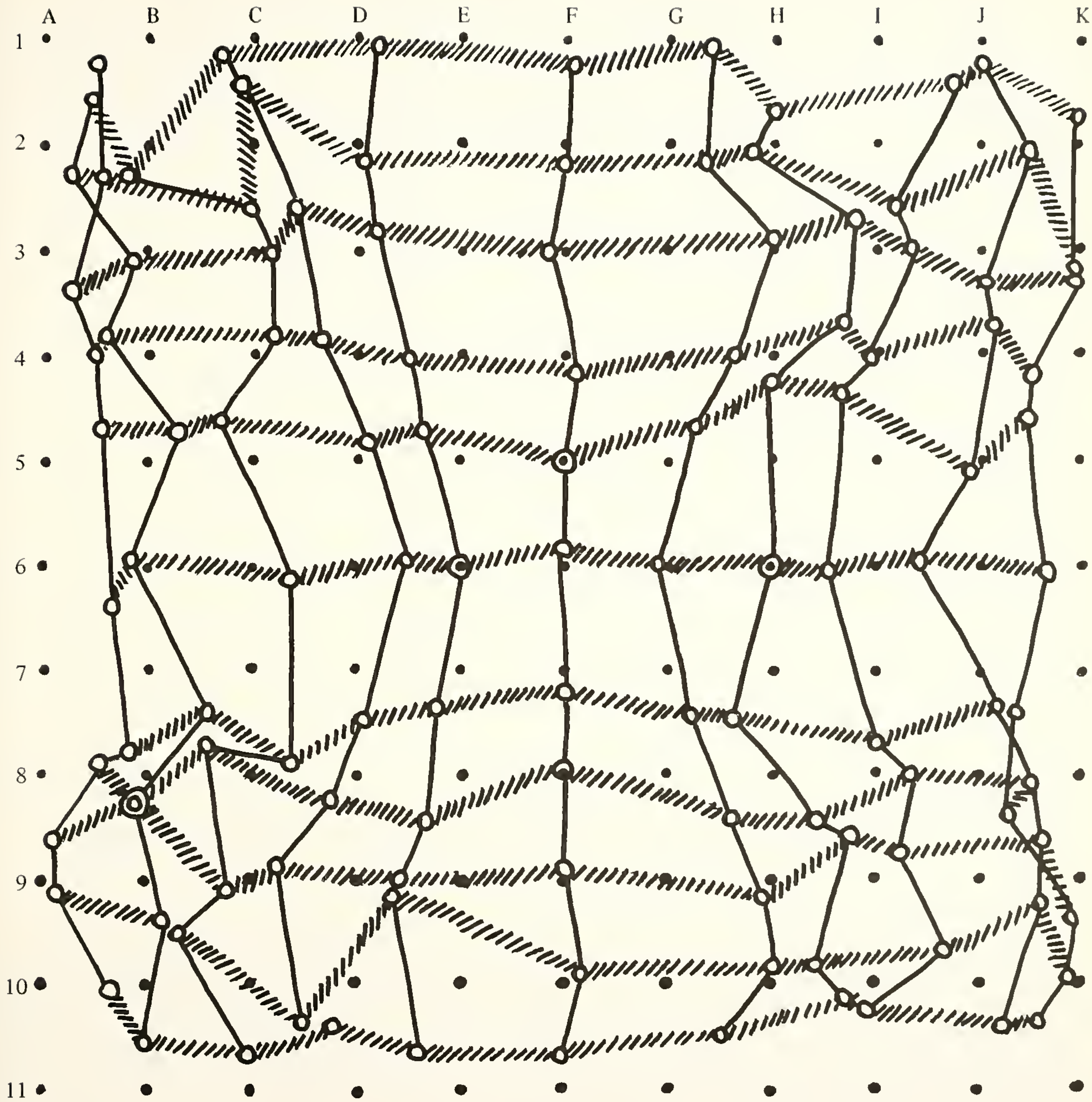


Figure 10. Results of Experiment Using Test Grid Shown in Figure 9
(Dark nodes represent original lattice points; white nodes, the average of the *S*s' responses.)

	A	B	C	D	E	F	G	H	I	J	K
1	.92	.67	1.25	1.19	.98	.30	.49	.63	.64	1.00	.30
	.40	.50	2.61	.30	0	.40	0	.66	.46	.30	.80
2	.92	.46	.45	1.14	1.14	.45	.46	.60	.83	.80	.30
	1.00	.78	.92	.49	.70	.83	.83	.77	.92	.63	.83
3	.64	.70	.75	1.20	.75	.30	.77	.60	.46	.77	.30
	.49	.54	.63	.49	.98	.94	.83	.80	.70	.98	.40
4	.50	1.02	.98	.78	.81	.30	.66	.64	.54	1.04	.92
	.45	.75	.87	.40	.45	.54	.54	.92	.94	.49	.54
5	.80	.90	1.00	.70	.49	0	.40	.54	.66	.83	1.02
	.46	.46	.49	.40	.46	0	.49	.60	.46	.77	.50
6	.78	.70	.66	.67	0	0	.30	.63	.81	1.02	.66
	.49	0	.30	.30	0	.60	.30	0	0	.30	0
7	.94	1.11	1.02	.70	.40	0	.40	.66	1.18	.75	.46
	.60	.66	.70	.49	.46	.40	.49	.49	.64	.46	.49
8	.80	.94	.66	1.08	.46	.45	.80	.49	.46	.50	.90
	.83	.78	.64	.98	.80	.54	.80	.66	.54	.89	.78
9	.30	.83	.75	.78	.66	0	.94	.64	.75	.66	.30
	1.00	1.19	1.04	.87	.77	.70	.54	.67	1.42	1.02	.90
10	.40	1.25	.64	1.20	.80	.40	1.00	.92	1.27	.66	.30
	1.22	.49	1.12	.66	.83	.54	.75	.87	1.02	.60	.83
11	.64	1.10	1.00	.75	1.11	0	.81	1.00	.94	.40	.66
	.83	.66	.46	.66	.46	.64	.92	.94	1.08	.80	.64

Figure 11. Standard Deviations in Units of the Lattice Distance

(The upper number represents the horizontal sample deviation; the lower number, the vertical one.)

Since the horizontal coordinate was constant for points on column F during the jump, *S* guessed it accurately. Similarly, he guessed the vertical coordinate of points on row 6 accurately. He overestimated the horizontal coordinate of the jump for all points on columns E and G. Similarly, he overestimated the vertical coordinate of the jump for all points on rows 5 and 7. Thus *S* exaggerated the distance of points near the center from the center. Because *S* was not allowed to guess points outside of the grid, the horizontal coordinate of the jump was underestimated for points on the vertical edges of the grid. Similarly, the vertical coordinate of the jump was underestimated for points on the horizontal edges of the grid. The near quadrantal symmetry of the mean response chart and the rough equality of the horizontal and vertical standard deviations suggest that the two coordinates are displayed equally well.

The last experiments measured the speed and accuracy with which handwritten letters could be transmitted.

The experimenter presented a letter to *S* by moving the probe to the start position for the letter, turning on the display, drawing the letter, and then turning off the display. Figure 12 shows a sample of the letters used (16). The letters were drawn in the center of the writing area with the aid of two horizontal guidelines which trisected this area. Letters like a, o, e, and so on were drawn between the two guidelines. Letters like b, d, k, and so on reached from the top of the writing

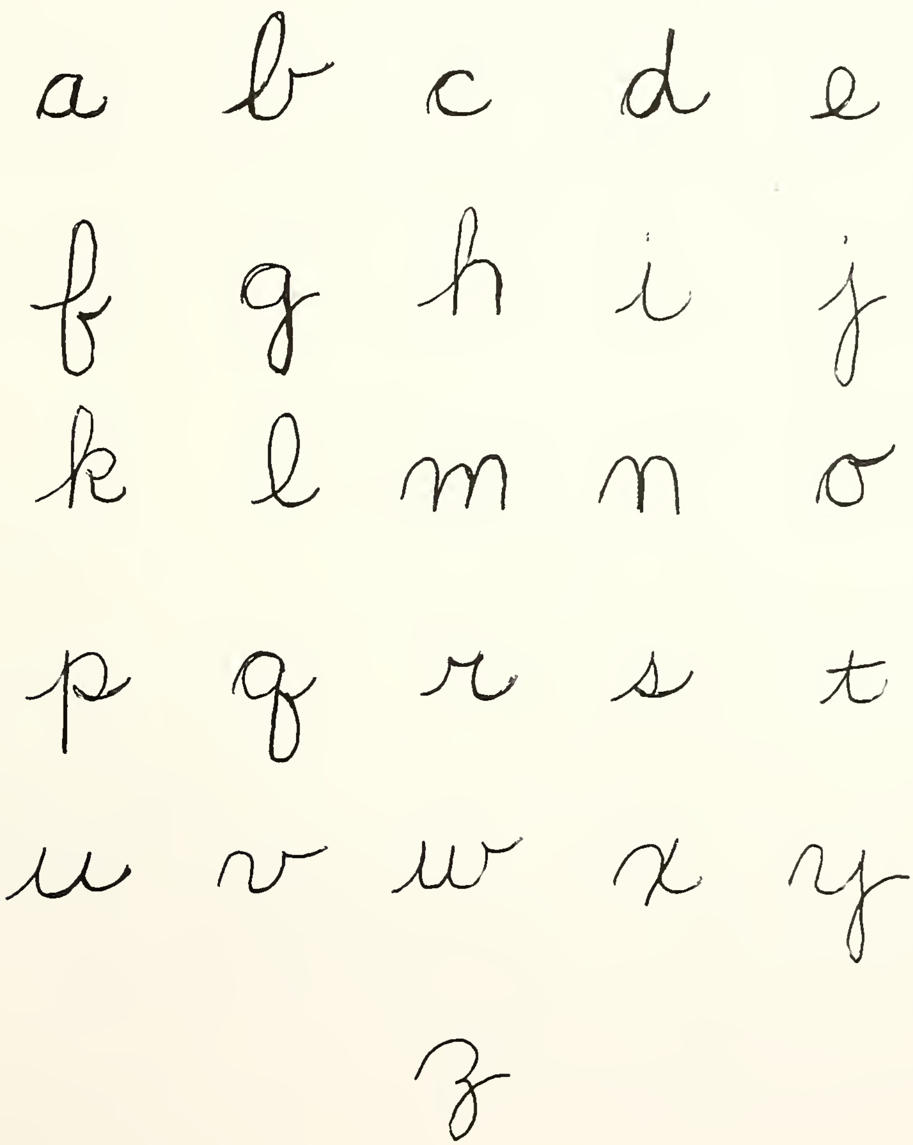


Figure 12. Handwriting Sample

area to the lower guideline. Similarly, letters like g, p, q, and so on reached from the upper guideline to the bottom of the writing area. The display switch was manipulated to turn off the sound during retrace on letters, such as i, j, t, and x, which require "dots" or "crosses." Writing speed was set by the experimenter.

During the training period *S* (there were three), seated as usual, was presented with a letter and asked to identify it. Errors were corrected immediately, and both the original letter and the letter that *S* had guessed were displayed for comparison. As *S*'s ability improved, letters were presented faster in an attempt to maintain speeds at the upper limit of *S*'s capacity. *S*s were given concentrated practice on troublesome letters. Practice was frequently interrupted for discussion.

A summary of the observations made during the learning period follows. Even with no training, *S*s could recognize letters at the rate of 3/min. As rates increased to 10 letters/min, *S*s stopped following the probe motion and began listening for "features" in the sound. After ten hours of practice *S*s were identifying 20 letters/min (17). An additional ten hours of practice did not increase the transmission rate any further. Increases in writing speed caused increases in response time, leaving the transmission rate nearly constant, but reducing accuracy.

Convinced that no rate increase was imminent, I decided to obtain some quantitative data on accuracy.

Each of the 26 letters was presented to *S* twenty-five times in random order. *S* was not informed when he mistook a letter. His response was the signal for presentation of the next letter. The results in "confusion matrix" form are shown in Figures 13, 14, and 15. Apparently because of the absence of feedback, errors propagated--that is, mistakes made early in the test were repeated throughout the test. To measure the effect of feedback, each *S* was given another test, similar to the preceding, in which errors were immediately corrected. An incorrect guess was followed by redisplay of the original letter and then the erroneous one. Under these conditions the total number of errors was nearly halved, as shown by Figures 16, 17, and 18.

In Figures 13 through 18 each number is the percentage of times the letter at the top of that column was mistaken for the letter to the right of that row (out of the 25 presentations of the letter above it). For example, in Figure 13, the letter "E" was mistaken 4 percent of the time for the letter "C."

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
																										A
																										B
				4																						C
						4								4												D
																										E
																4										F
																16										G
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							4													52						N
	4																									O
					4																					P
						4																				Q
		8								12																R
		28																								S
																										T
													12													U
													4													V
													4													W
																			8							X
						4																				Y
																									4	Z
					4	4	4							4											4	BK

Figure 13. Results of Letter Recognition Experiment

(Subject R.B., without knowledge of results. Speed: 19 letters per minute; error: 8.3 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
		4					4											8								A
			8		4		12							4												B
4																		60			4					C
																										D
																										E
																										F
																28										G
	4				40					4																H
																										I
																										J
															8											K
				4																						L
																										M
																				32						N
	4																									O
																										P
						4												4								Q
		12																								R
		40																								S
									4														24			T
												4	52											4		U
														16								4				V
												4														W
																										X
																										Y
																								16	4	Z
																										BK

Figure 14. Results of Letter Recognition Experiment

(Subject J.F., without knowledge of results. Speed: 17.5 letters per minute; error: 16.5 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
						4														4						A
							4																			B
8																		4								C
4																										D
											4															E
										4																F
																20										G
	8																									H
									4																	I
																										J
					12		4																			K
																										L
																										M
		4															4			48						N
																										O
																										P
						12																				Q
													4								4					R
													4												4	S
																										T
													32				8									U
													4	4												V
																										W
																										X
						4																				Y
					4																					Z
	4			4											4										4	BK

Figure 15. Results of Letter Recognition Experiment

(Subject G.G., without knowledge of results. Speed: 18.3 letters per minute; error: 9.25 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
																										A
																										B
																	4	4								C
																										D
											4															E
																										F
																										G
	12																									H
																										I
								4																		J
																										K
																										L
																										M
																				20						N
			4													4										O
																										P
																										Q
		8																								R
		12																								S
																										T
													8													U
																										V
																										W
																										X
																										Y
																								4		Z
	4																								4	BK

Figure 16. Results of Letter Recognition Experiment

(Subject R.B., with immediate error correction. Speed: 18.3 letters per minute; error: 3.75 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
																										A
																										B
																		40								C
														4												D
																										E
							4																			F
																28										G
	8				24										4											H
																										I
								4																		J
																										K
				8																						L
4																										M
																				40	4					N
4																										O
																										P
																										Q
		4																								R
		8			4																					S
																							8			T
													56													U
	4													4												V
												4														W
																										X
																										Y
					4																			4		Z
																										BK

Figure 17. Results of Letter Recognition Experiment

(Subject J.F., with immediate error correction. Speed: 16.25 letters per minute; error: 10.7 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
																										A
																										B
																		8								C
																										D
																		4								E
																										F
																4										G
					4																					H
																										I
																										J
																										K
																										L
																										M
																	4			48						N
			4														4									O
																										P
																										Q
													4							4						R
		16																								S
																										T
		4										4	36													U
																										V
																										W
																										X
						8																				Y
																										Z
																									4	BK

Figure 18. Results of Letter Recognition Experiment

(Subject G.G., with immediate error correction. Speed: 18.3 letters per minute; error: 6.3 percent.)

A small group of letters accounted for almost all of the errors. The common errors are listed below.

b was called h
c was called r, s
f was called h
n was called u
q was called g
s was called o
u was called n

An interesting feature of this table is its asymmetry. For example, b was frequently called h, but not vice versa. I speculate that *S* separates b and h by the presence of a feature such as the tail on the b. This feature may be missed when present, but is never heard when absent.

All *S*s had the most difficulty distinguishing between the u and the n. Figures 21 and 22 show that both the vertical and horizontal coordinates of the u and n are indeed similar. All *S*s claimed that they were just guessing on these letters. However, one *S* made only seven u-n confusions--more than five standard deviations (3-1/2) from the expected twenty-five, if guessing was indeed random (18).

Figures 19 through 23 show the horizontal and vertical coordinates of the probe tracing each letter as a function of time. The upper trace in each pair is the vertical coordinate. The lower one is the horizontal coordinate with right plotted positively.

Because of the redundancy present in written letters, I expected that the horizontal signal could be eliminated without greatly affecting performance.

To check this hypothesis, the pickup string was removed from the horizontal pickup pot, and the pot was set to its center position. Each *S* was given 1/2 hr of practice following the procedure described earlier in conjunction with the initial training period. It was evident that elimination of the horizontal had little effect on the transmission rate. A test with error correction, identical to the one last described, was given to each of the three *S*s to see whether accuracy suffered. The results are tabulated in Figures 24, 25, and 26.

Although each *S* did worse without horizontal information than he did with it, the fractional increase in errors was greatest for the *S* who had the lowest error rates. All letters previously frequently confused were still frequently confused when the horizontal information was removed. In addition, the following new confusions were introduced.

f was called p, z
g was called y
r was called c
v was called o
y was called f, g, z

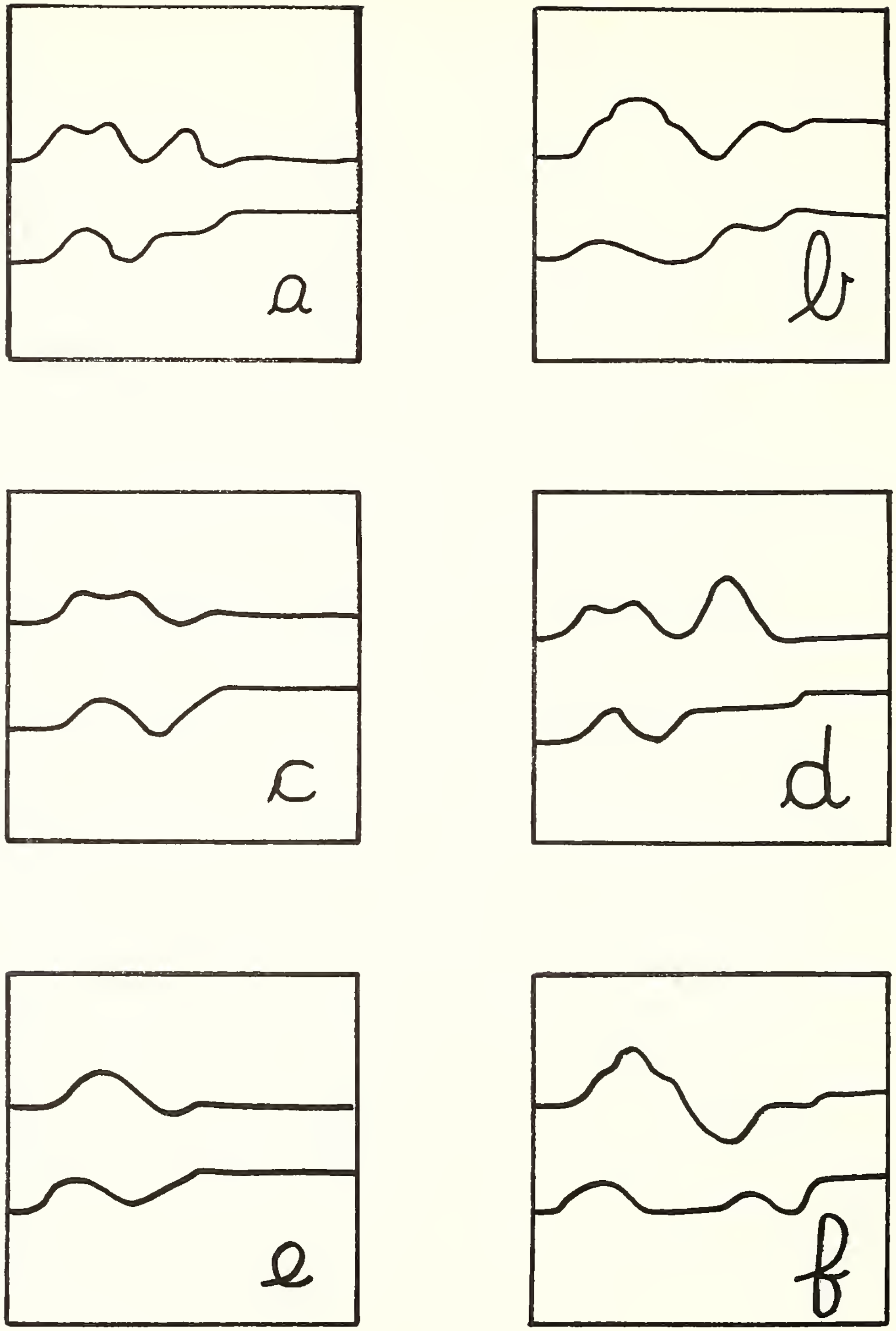


Figure 19. Coordinates of Letter Traces As a Function of Time

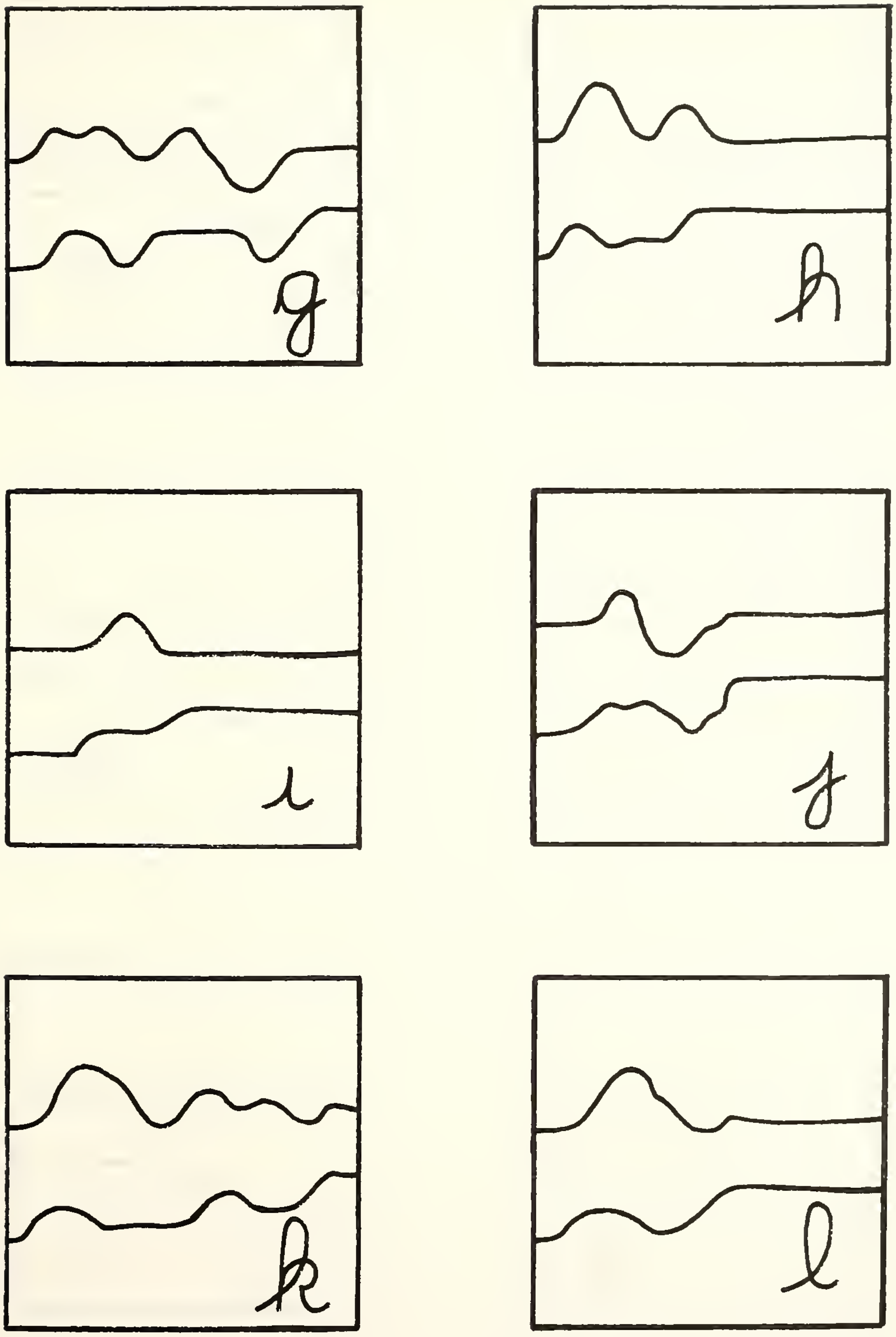


Figure 20. Coordinates of Letter Traces As a Function of Time

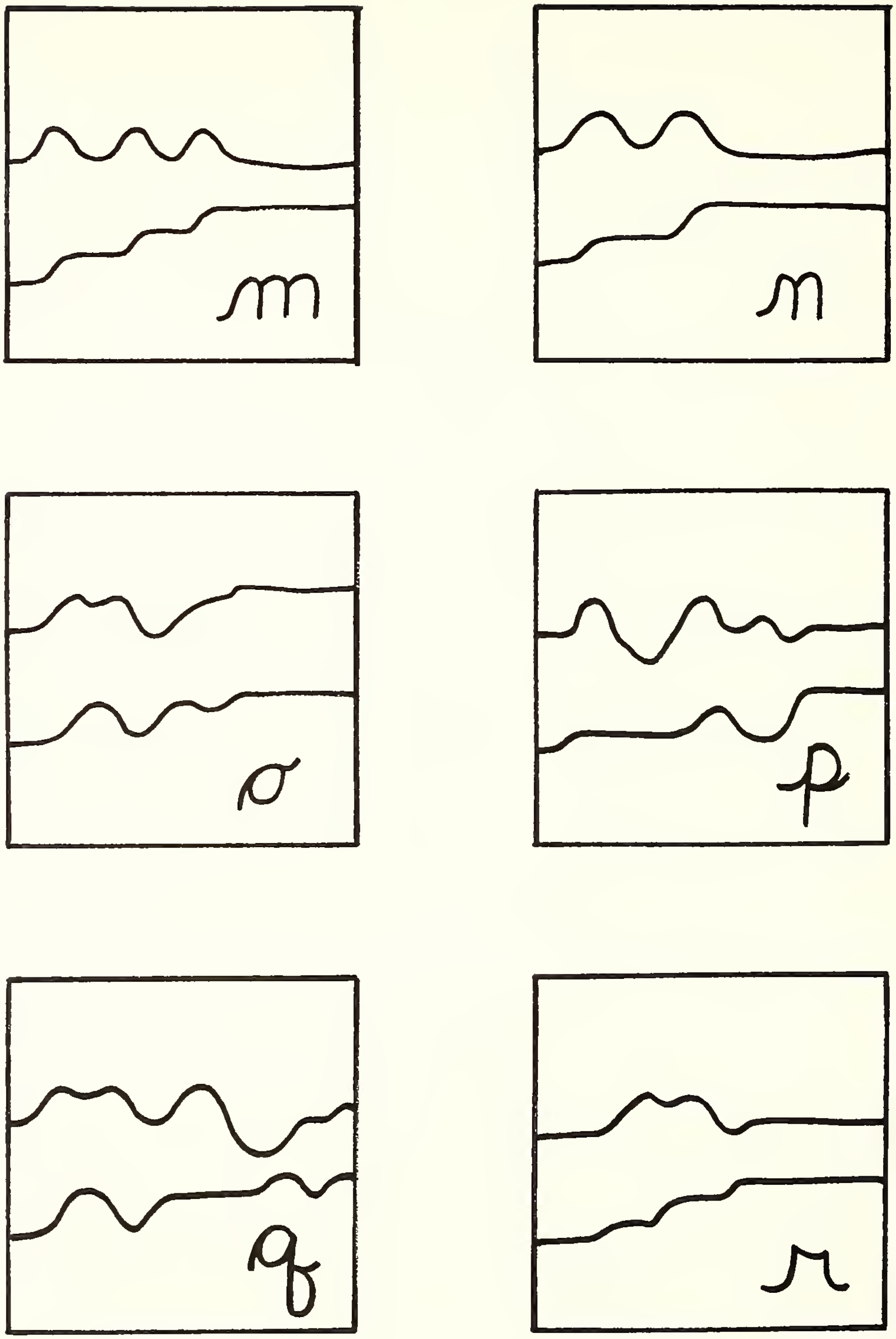


Figure 21. Coordinates of Letter Traces As a Function of Time

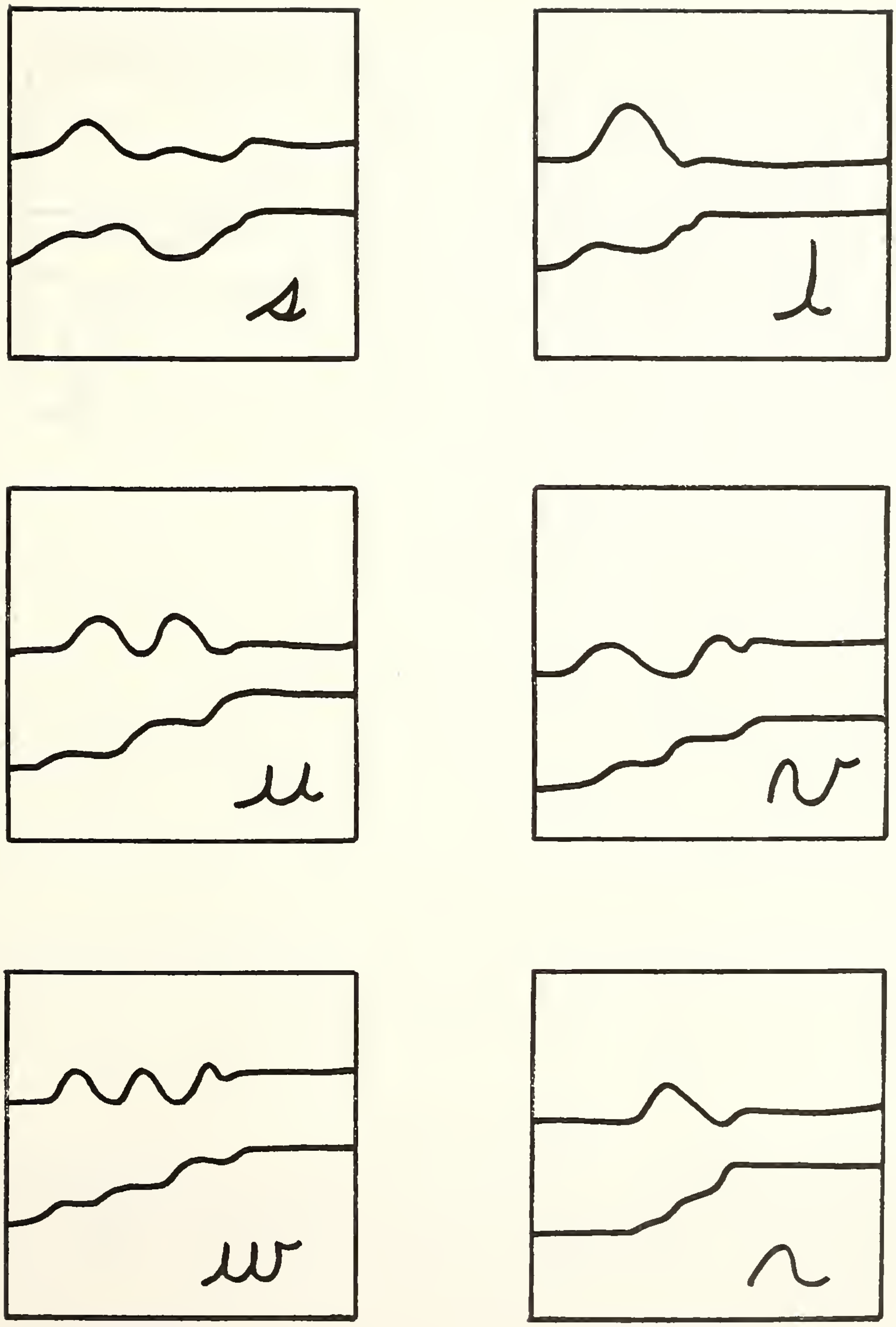


Figure 22. Coordinates of Letter Traces As a Function of Time

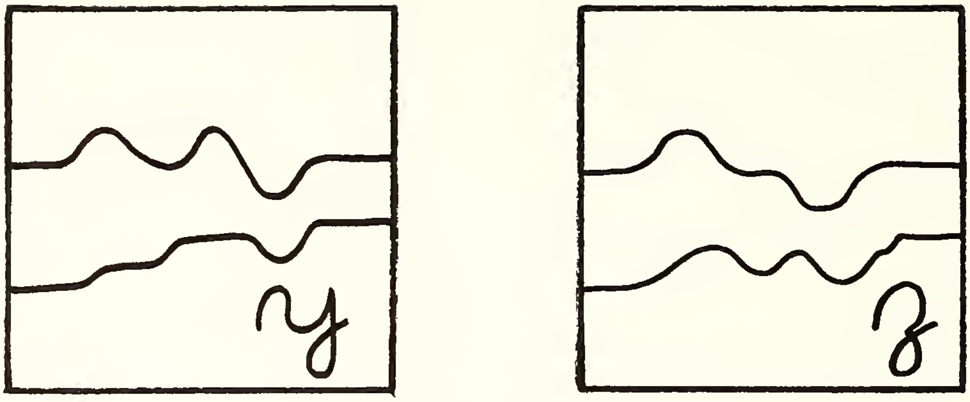


Figure 23. Coordinates of Letter Traces As a Function of Time

The r-c pair was nearly impossible to separate. Moreover the number of u-n errors increased for all *S*'s.

By taking into account the nature of the errors in the preceding tests, *S*s descriptions of their decision processes, and the geometry of the letters, I compiled the chart shown in Figure 27. It represents my best guess as to the nature of the recognition process as applied to letters. All *S*s deviated from this schema occasionally, and some *S*s could not make certain of the distinctions shown on the chart.

The preceding experiments with letters suggest that this display is not competitive with other aural codes (such as Morse Code) in either speed or accuracy. However, if it is to be used for transmitting words, then a pitch-only display (which is much simpler to instrument) is certainly adequate.

CONCLUSIONS

The experiments discussed in the body of the thesis led to the conclusions listed in the introduction. Care must be taken not to interpret these conclusions in any wider context than that justified by the experiments.

The display is a new sensory presentation and thus can be used for an infinitude of new psychophysical experiments. I selected some experiments that were particularly interesting, because they were related to certain tasks for which the display might prove suitable.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
																	4									A
																										B
																	8									C
4																										D
																										E
	4																									F
					4											4								12		G
	4																									H
																										I
						4																				J
															4											K
																										L
																										M
														4						44						N
4																					16					O
4																										P
																										Q
		80																								R
		4			8																					S
																										T
		4											60													U
																										V
												4														W
																										X
						4																				Y
					8													4						8		Z
4					4															4				4		BK

Figure 24. Results of Letter Recognition (Pitch Only) Experiment
(Subject R.B., with immediate error correction. Speed: 17 letters per minute; error: 12.7 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
		4																								A
							4																			B
																	52	32								C
														8												D
																		4								E
				4																				12		F
																12								4		G
	4				20										4											H
																										I
																										J
																										K
				4																						L
4																										M
																				64						N
4																										O
																										P
						4																				Q
		12																8								R
		8															4									S
					4			4																		T
													44													U
	4													4												V
														8												W
																										X
						8																				Y
																								4		Z
		4																								BK

Figure 25. Results of Letter Recognition (Pitch Only) Experiment

(Subject J.F., with immediate error correction. Speed: 12.5 letters per minute; error: 14 percent.)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
		4																4								A
																										B
																	76	8								C
																										D
											4							4								E
																										F
4																4								4		G
	16																									H
									4																	I
																										J
																										K
																										L
																										M
																	4	4		80						N
																					12					O
					28																					P
																										Q
		24											4					12								R
																	4									S
																										T
													24													U
													4							4						V
														4												W
																										X
					4																					Y
					4													4								Z
																										BK

Figure 26. Results of Letter Recognition (Pitch Only) Experiment

(Subject G.G., with immediate error correction. Speed: 17.5 letters per minute; error: 13.5 percent.)

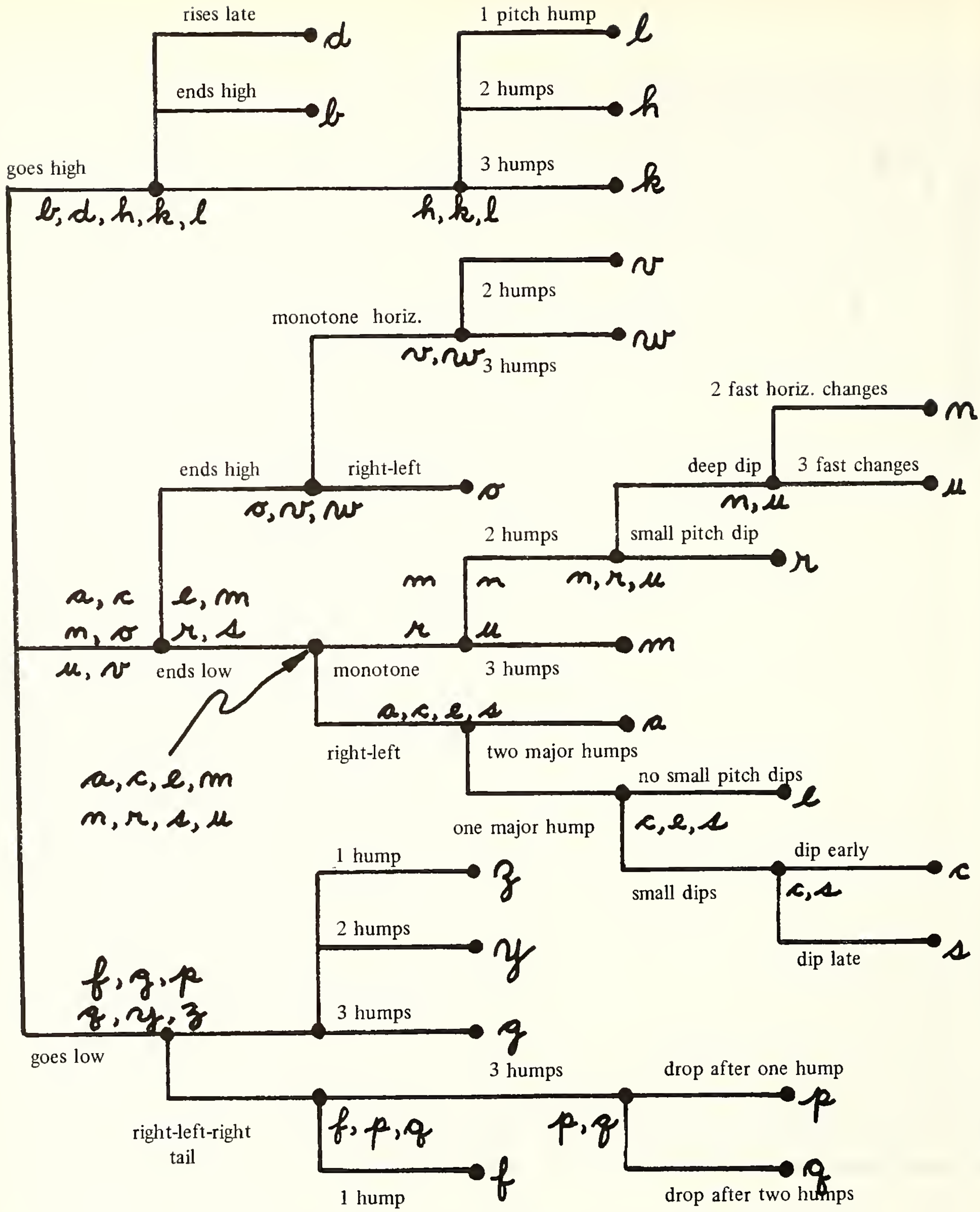


Figure 27. A Decision Tree

APPENDIX: EQUIPMENT

The Input Board

The input board is shown in Figure 28. Motion of the probe on the 3-1/2 in. x 3-1/2 in. writing table is decomposed into x and y components by the pulley-string-pot system. Line tension is maintained by rubber bands. The pots are ball bearing servo-pots with low friction under lateral shaft loading. Also mounted on the input board is a temporary off switch permitting silence between trials.

The y-*Axis Pickup*

The vertical pickup is resistor loaded, producing an output voltage that is nearly exponential in y. As y varies from 0 to 1, the output voltage runs through two octaves from -12 to -3 V.

The Pitch Generator

The vertical output voltage is fed through an isolating emitter follower to a special astable multivibrator. This multivibrator oscillates with a period proportional to the magnitude of the control voltage. It operates by discharging, at a constant rate, timing capacitors whose initial voltage is the pot output voltage. Pertinent circuit diagrams are shown in Figures 28, 29, and 30. Initializing of the timing capacitors is done through the diodes. Two transistors used as current sources do the draining. There are two points worth noting concerning this circuitry. First, for proper operation, it is essential that the two power supply voltages be identical. Second, the temporary off switch operates by shunting one of the timing transistor collectors to ground. This changes the mode of oscillation and prevents triggering of further stages--while making lockup impossible.

The x-*Axis Pickup*

The horizontal pickup pot drives two differential amplifiers through isolating stages. One of the amplifiers controls the delay chains. The other amplitude modulates the output pulses.

The Delay Chains

There are two delay chains--one for left and one for right. Each chain consists of two one-shot multivibrators. These one-shot multivibrators generate a delay proportional to their control voltage by precisely the same technique employed in the pitch generator. Two one-shot multivibrators are necessary per chain, since the delay time may exceed a pitch period. The control voltage is derived from the delay differential amplifier (Figures 28, 29, 31, and 32).

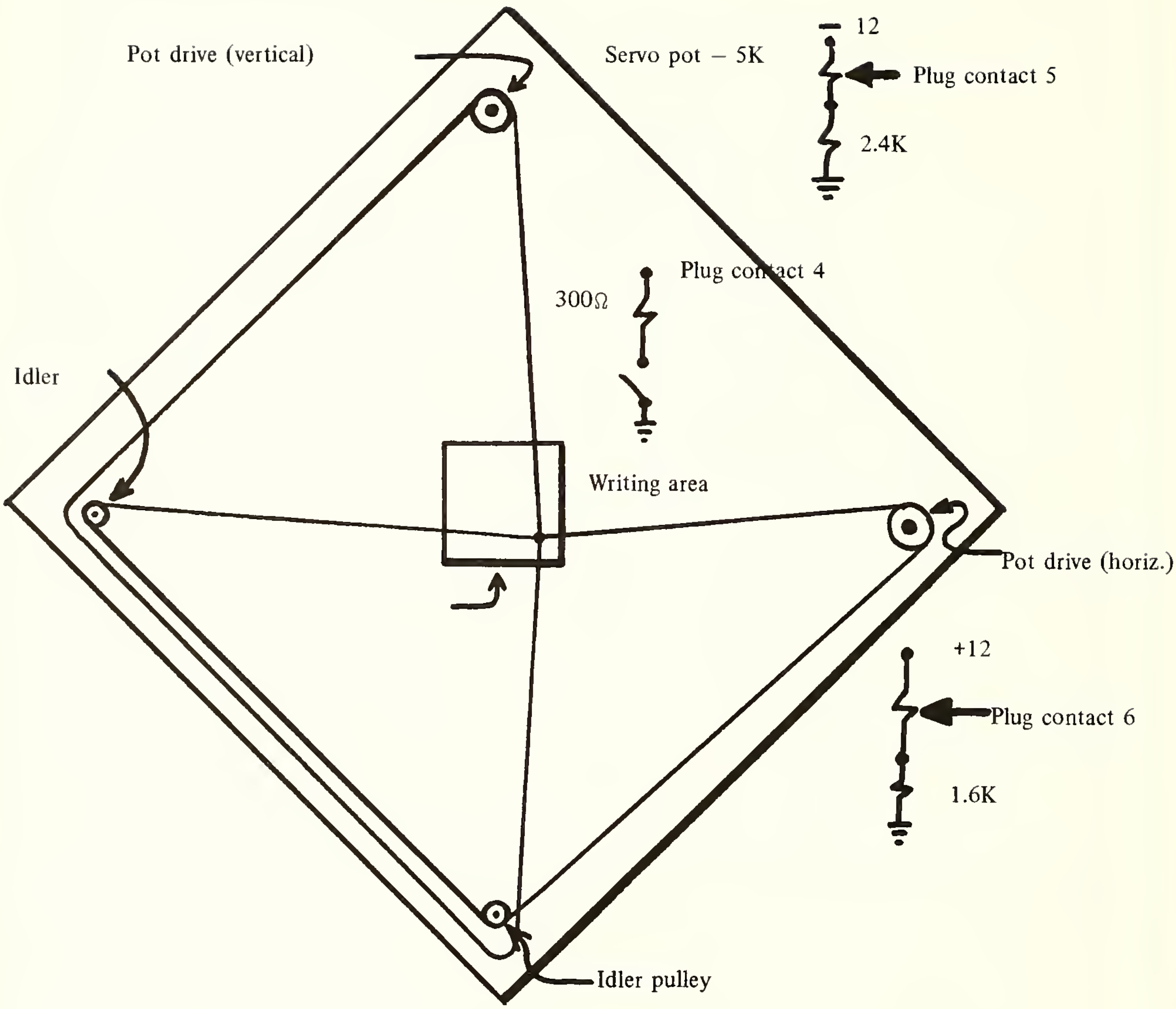


Figure 28. The Input Board

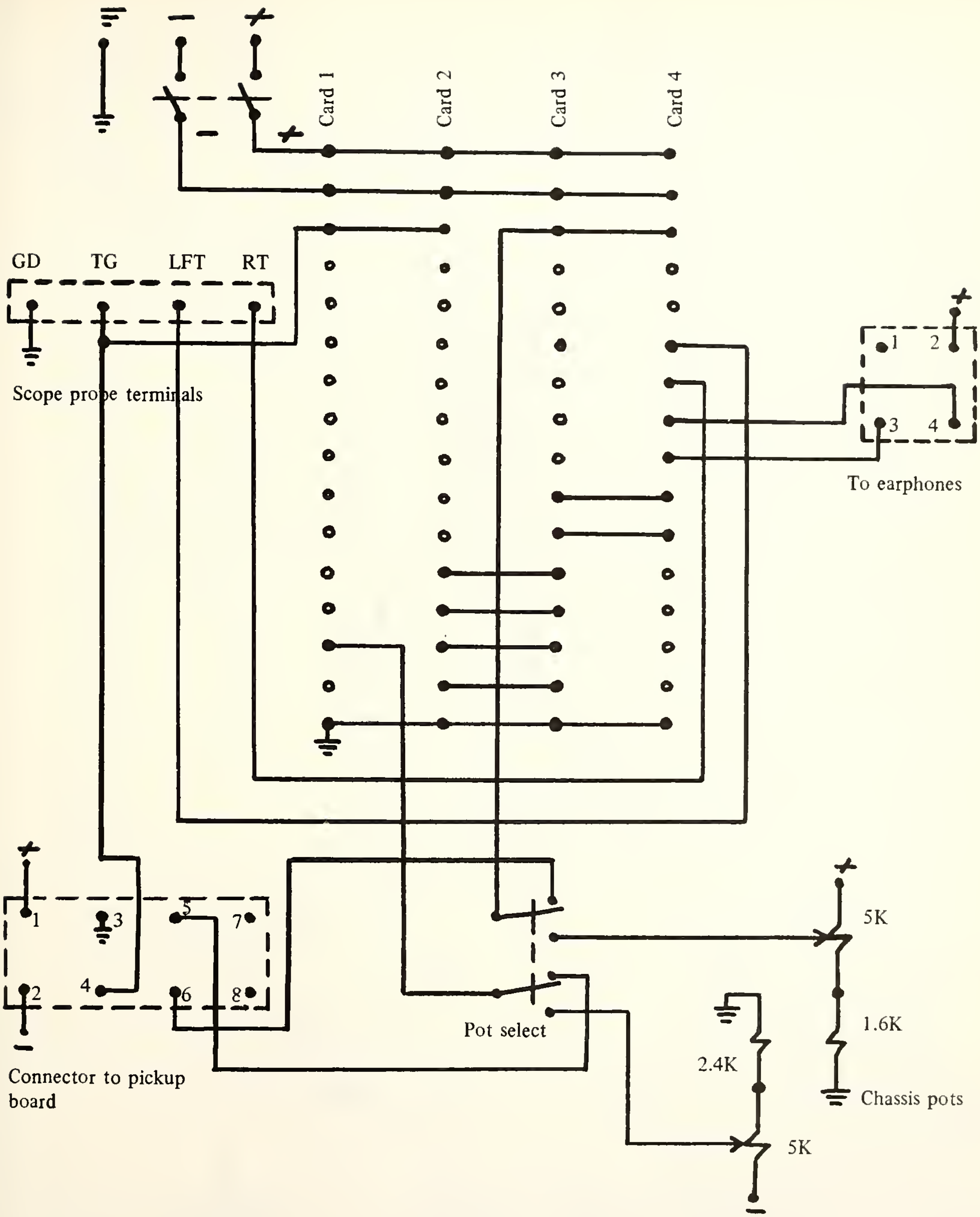


Figure 29. Chassis Wiring

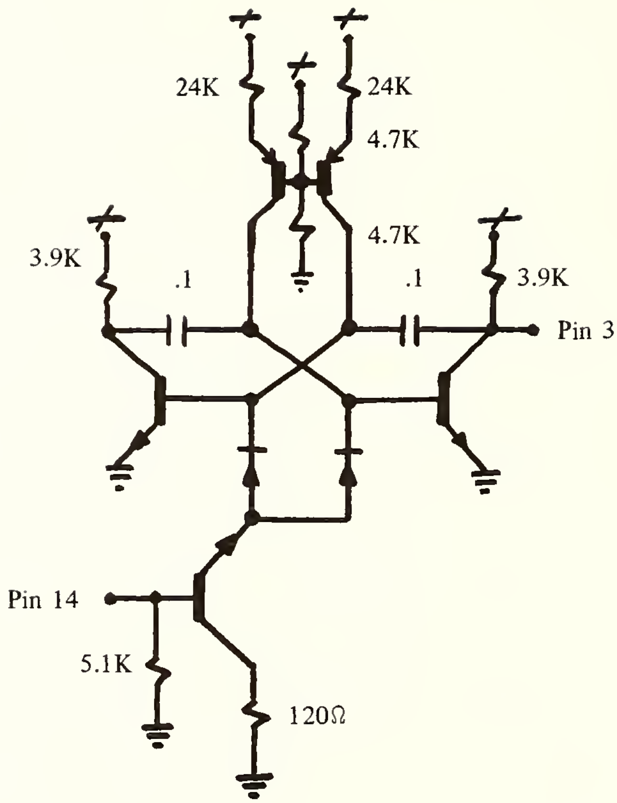


Figure 30. Variable Frequency Oscillator and Isolation Amplifier

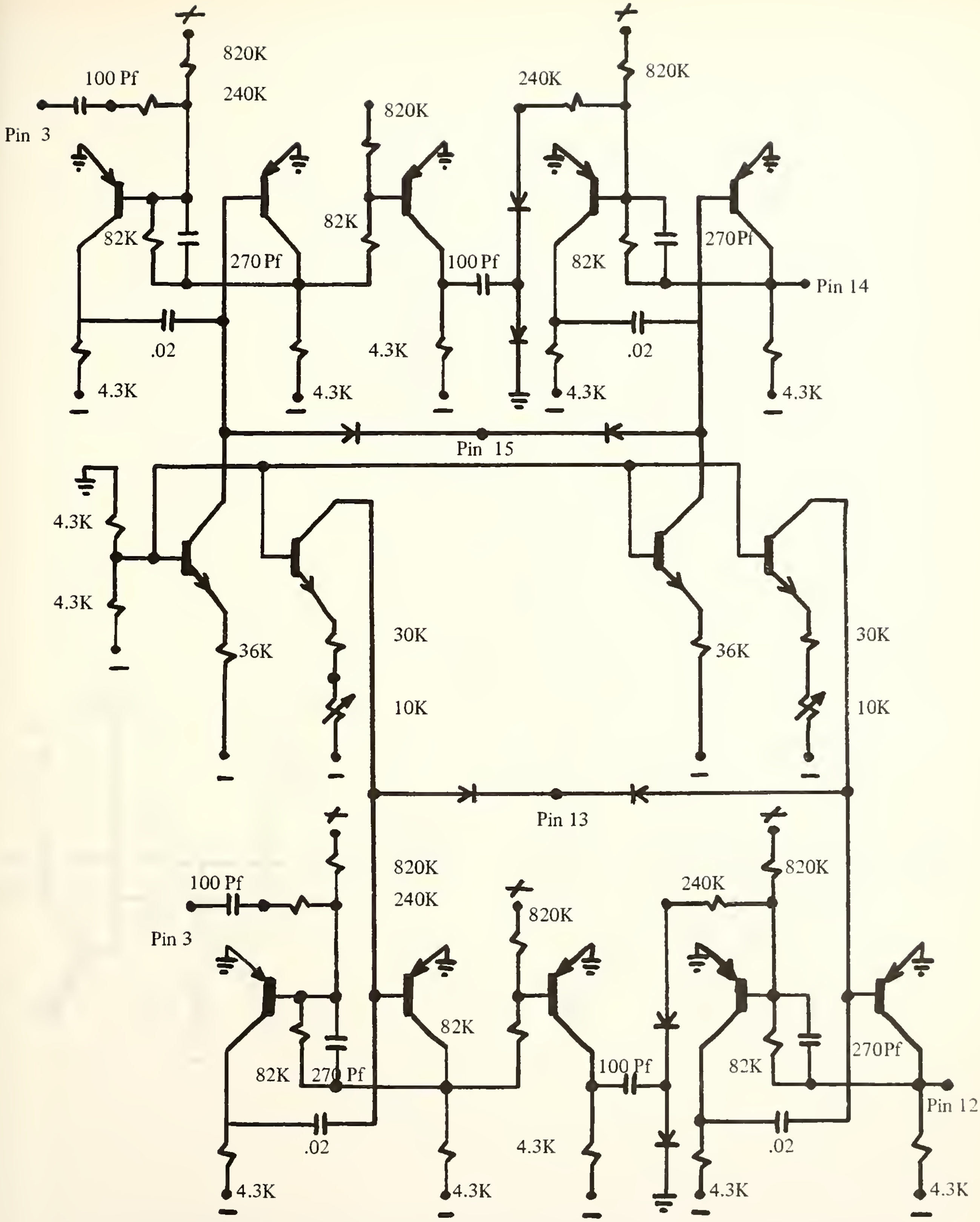


Figure 31. Two Delay Pairs

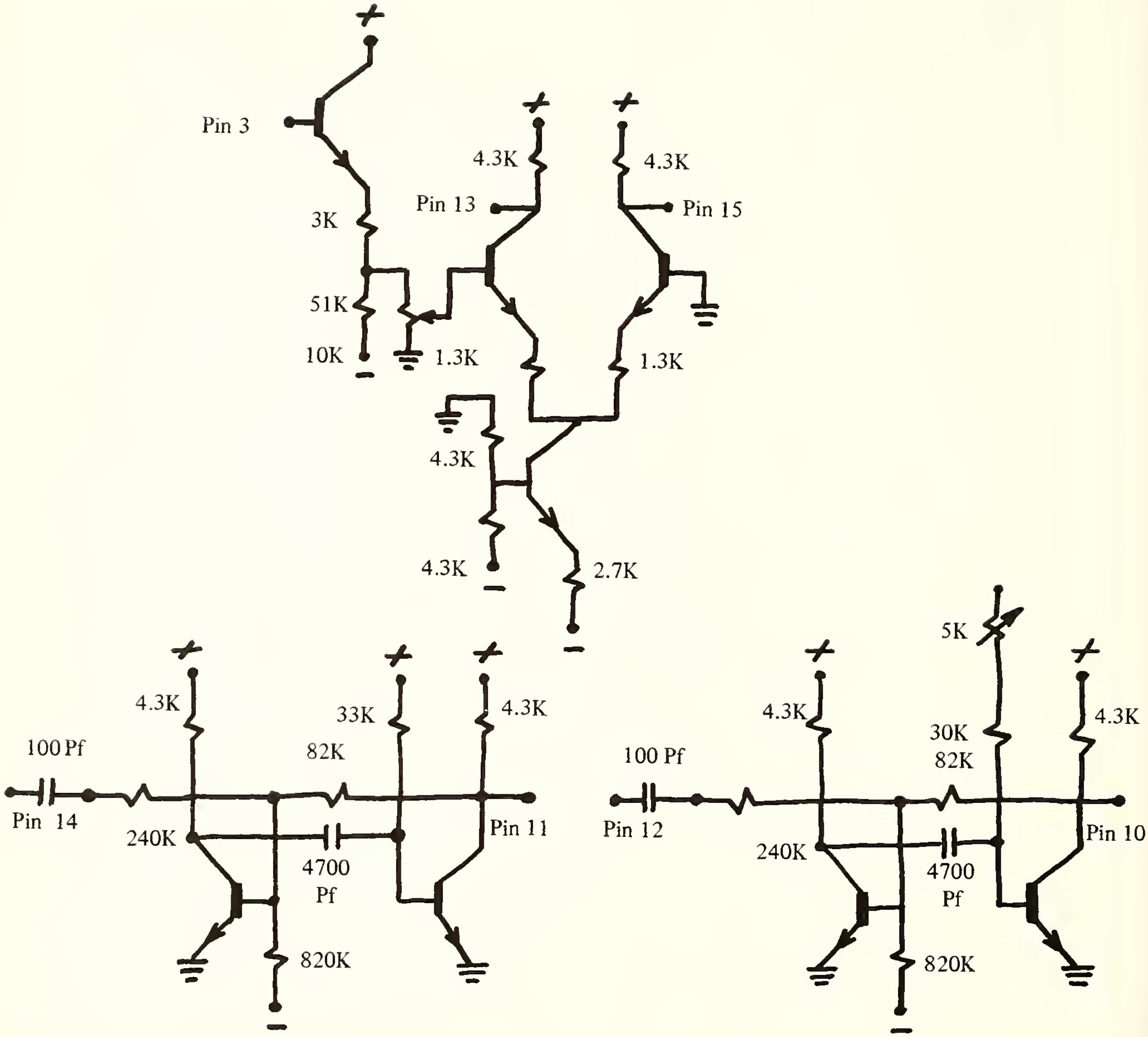


Figure 32. Two Pulse Formers and a Delay Amplifier

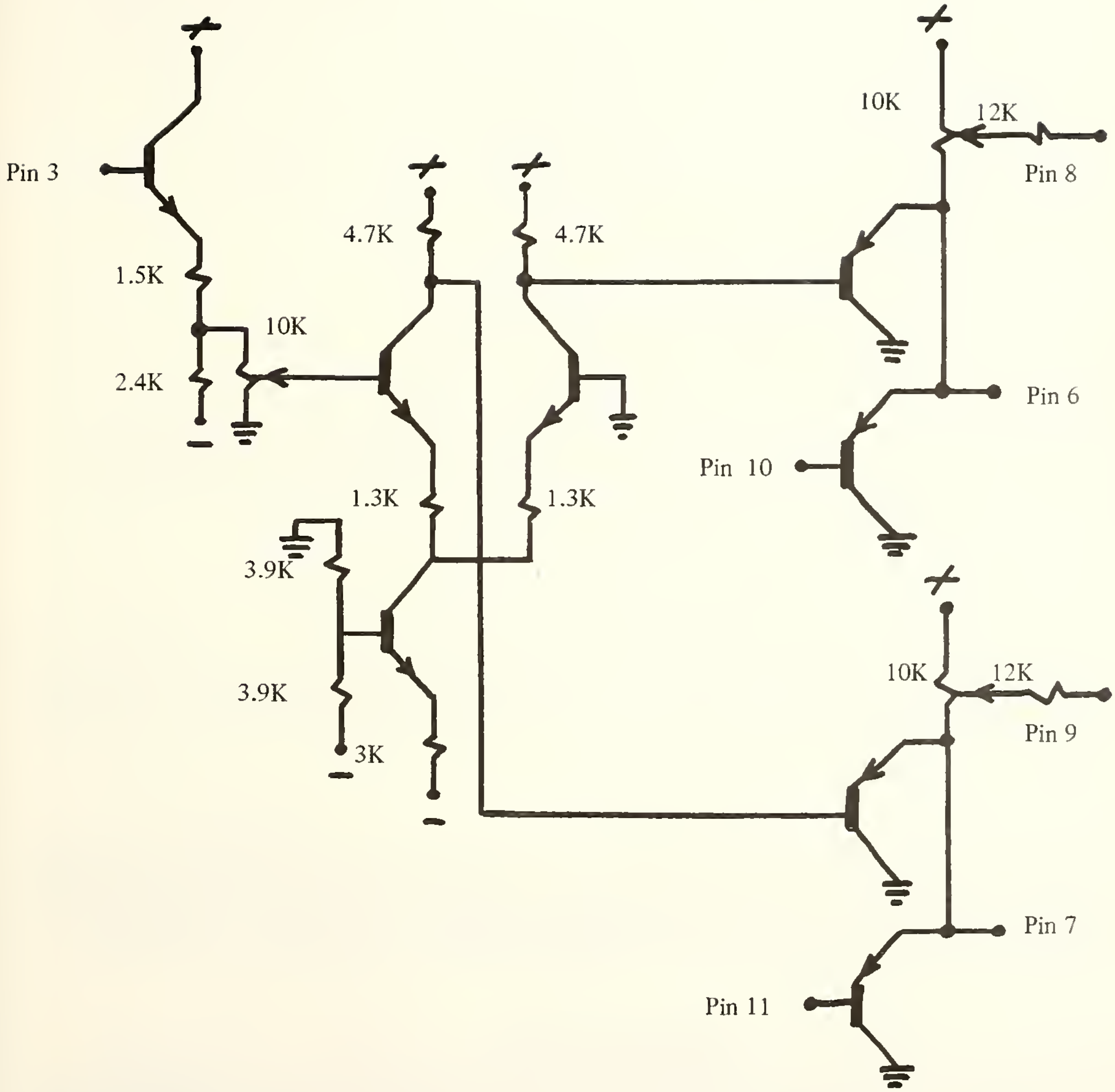
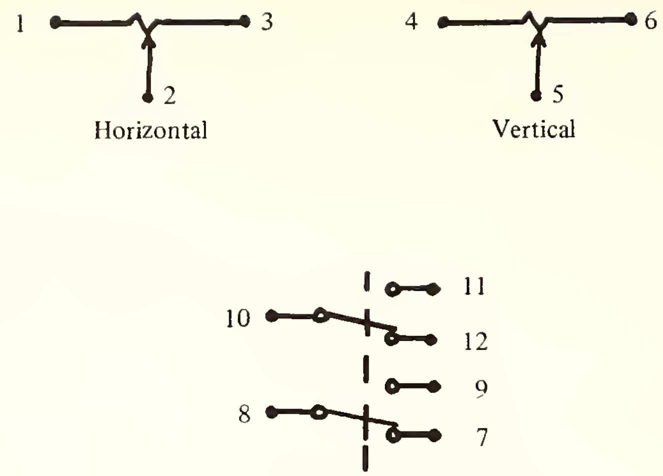


Figure 33. Isolation AMP, Modulation AMP, and Amplitude Modulators



Switch shown in the
"Temp. Off" position

Figure 34. Pickup Board Modification

(A late modification of the pickup board makes it possible to employ the pots and switch for other purposes. Turning the extrn-acoustic switch to the extern position connects the vector board socket as shown.)

Pulse Formers

Each delay chain triggers a standard one-shot multivibrator. Thus the outputs of the two pulse formers are two pulse trains with equal amplitude and pulse width, and a relative time shift. (See Figure 32.)

Amplitude Modulators

The four modulator transistors chop off the formed output pulses at levels set by the amplitude-modulation, differential amplifier. (See Figure 33.) These pulses are then supplied to the earphones via the two volume controls.

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3. *Flying by Auditory Reference.* OSRD Report No. 5123, June, 1945, Office of Scientific Research and Development, National Defense Research Committee, Division 17, Section 17.3.

4. J. C. R. Licklider. "Basic Correlates of Auditory Stimulus," in Stevens (ed.), *Handbook of Experimental Psychology.* New York: Wiley, 1951, pp. 985-1039.

5. A. W. Mills. "Auditory Perception of Spatial Relations," in L. L. Clark (ed.), *International Congress on Technology and Blindness*, Vol. II. New York: American Foundation for the Blind, 1963.

6. A. W. Mills. "Lateralization of High Frequency Tones," *J. Acoust. Soc. Am.*, Vol. 32, p. 132.

7. A. W. Mills. "On The Minimum Audible Angle," *J. Acoust. Soc. Am.*, Vol. 30, No. 1, p. 237.

NOTES

1. See Reference 4.

2. See Reference 2.

3. See Reference 5.

4. See Reference 4.

5. These choices were suggested by experiments with a prototype system.

6. These choices were suggested by experiments with a prototype system.

7. See Reference 6.

8. See Reference 2.

9. This discussion ignores the presence of amplitude modulation. Probably the amplitude modulation keeps the sound fused even for relative delays in excess of $2k$.

10. Audiometer tests were taken in a noisy room with an old audiometer. Consequently I accepted *S*s as normal if their hearing tested within 15 db of normal, showed no violent changes with frequency, and differed by no more than 10 db between ears. Perhaps this precaution was unnecessary since an *S* having marked hearing loss apparently does as well with the display as a normal subject.

11. Precision of localization is best for sources on the median plane and worst for those far right or left (see reference 7). Moreover, *S* could easily locate his median plane, but had no anatomic feature delineating the midleft and midright positions.

12. Were setting error Gaussian (it is not), then 0.35 times the range approximates the standard deviation with 0.9 efficiency.

13. Reference 3 mentions a similar experiment in which "false centering" was noted.

14. This tendency for one aspect of a complex sound to dominate was also noted in several experiments described in reference 3.

15. Loudness increases with pitch because the pulses of constant energy occur more frequently.

16. For a time, early in the experiment, slanted letters were used. *S*s performed equally well on both, but vertical letters were standardized for the rest of the experiment.

17. All rates were computed by dividing the total time by the total number of letters for a presentation of at least 130 letters. The time included the *S*'s response time and any extra corrective letter displays.

18. A friend with perfect pitch was able to distinguish u from n perfectly at 15 letters per minute, but unfortunately I could not retain him as a subject.

ELECTRICAL STIMULATION OF THE VISUAL APPARATUS

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Abstract

The visual cortex can be coupled to the environment through sensors (for example, photodetectors, sonar) by exploiting the phenomenon of phosphene production ("seeing stars") using electrical, electromagnetic, or pressure stimulation. Information capacity of this mode is greater than suspected, and the phosphene approach might offer a means of aiding the visually impaired.

A reliable method of coupling the visual cortex of the brain to extracorporeal nonphysiological receptors, without interfering with other sensory modalities, is needed. Many environmental sensors are available which use tactile or auditory pathways as the mode of information input to the brain (1). Electrical stimulation of the visual apparatus, although a procedure of some antiquity, was not incorporated in research toward extending human perceptive abilities until recently. This report presents a survey of the pertinent facts and progress in the field of indirect electrical stimulation of the visual cortex.

Sensations of "light" can be produced by passage of about 0.3 milliamperes through the head using external electrodes or by 1000 oersteds from induction coils a few millimeters from the skull. Some of the earliest experiments with electricity on the human body and the first cautious suggestion that the use of electrical stimulation might relieve blindness was made by Benjamin Franklin in 1751 (2). A few years later Le Roy reported the induction of flashes in a blind patient using a Leyden jar discharge (3). The electrophysiology associated with electrical stimulation of the visual apparatus was studied by Volta who experienced a flashlike sensation of light (known as Purkinje patterns, or more commonly as phosphenes) when a small potential difference was induced between his eyelids and some other part of his body (4). During the nineteenth century the phenomenon of pressure [deformation phosphenes (5)], or electrically induced flashes, was investigated by Brennen, Du Bois-Reymond, Finkelstein, Helmholtz, Muller, Purkinje, Ritter, and others (6). The phenomenon of flash sensation was also elicited using induction coils not touching the head by d'Arsonval (7) in 1896 and later, independently, by Thompson (8).

Since these discoveries a few careful investigations of electrical (9) and magnetic (10) stimulation of man's visual apparatus have been made. The flash sensation phenomenon has been generally accepted as the result of retinal stimulation by a current emanating radially from the electrode through the eye globe (11). The conclusion that electrically-induced phosphenes are mediated solely by the retina should be qualified. Russian workers demonstrated in the 1930s that phosphenes can be electrically induced in patients after enucleation but before optic nerve degeneration (12). However, only with an intact retina do the thresholds of electrical sensitivity remain normal, and only with a well-preserved, attached retina are the normal adaptive changes in electrical sensitivity present (13). Fortunately, even if the retina were necessary for the induction of phosphenes, most blind patients have intact retinas and might benefit from a device that along with normal head scanning proprioception produces a pattern of light suggestive of the shape of objects in the environment. Atrophy of the retina of an eye with a severe visual defect might be circumvented by periodic electrical stimulation.

The direct approach to stimulation of the visual cortex by implanted electrodes was suggested by the pioneering work of Penfield (14) and implemented in an attempt to build a visual prosthesis by Button and Putnam in 1961 (15). This approach had some success as has electrode implantation in the eighth cranial nerve for auditory stimulation (16), but the problems of such implantation at present appear to outweigh the ultimate practicality of this approach as a means of communicating with the brain.

Other than Barnard's suggestions in 1947 (17), little has been reported regarding the practical use of electrical stimulation of the visual apparatus, and there was little active research until recent years. In 1964, Baccaquer (3) discussed the phenomenon of phosphene production by inducing alternating current in the head and suggested that a transistorized photodetector device might be used as an aid for the blind. Such a system has been developed independently by us and prior to our efforts by a group at the University of Mexico headed by Dr. Armando del Campo. These investigations have raised the question of whether the sensation of light produced in either blind or normal subjects is entirely phosphenes or might be mediated by a pathway from the supra- or infraorbital branches of the trigeminal nerve to the visual tract perhap via the reticular formation (18). This possibility has not yet been thoroughly investigated, but the fact that visual impressions can be produced in blind patients as reported by the University of Mexico studies, and our studies in children with retrolental fibroplasia, prompts us to report some facts and ideas regarding the practical implementation of electrical and particularly electromagnetic stimulation of the visual cortex.

The sensation of a light flash may be elicited by application of 2 to 4 V potential difference across the head using a 1-cm metal disk electrode on a ciliary arch or forehead and a similar electrode placed on the back of the neck (Figure 1). Electrolyte paste or sodium chloride solution is used to establish less than 10,000 ohms resistance. A sensation of "flash" is generated on making or breaking the circuit (rise time should be less than 100 millisec). A flicker phenomenon can be generated by pulse trains or AC stimulation (fusion cannot be obtained at 60 cps--normal upper limit for photic stimulation); chronaxie is about 1 msec (19).

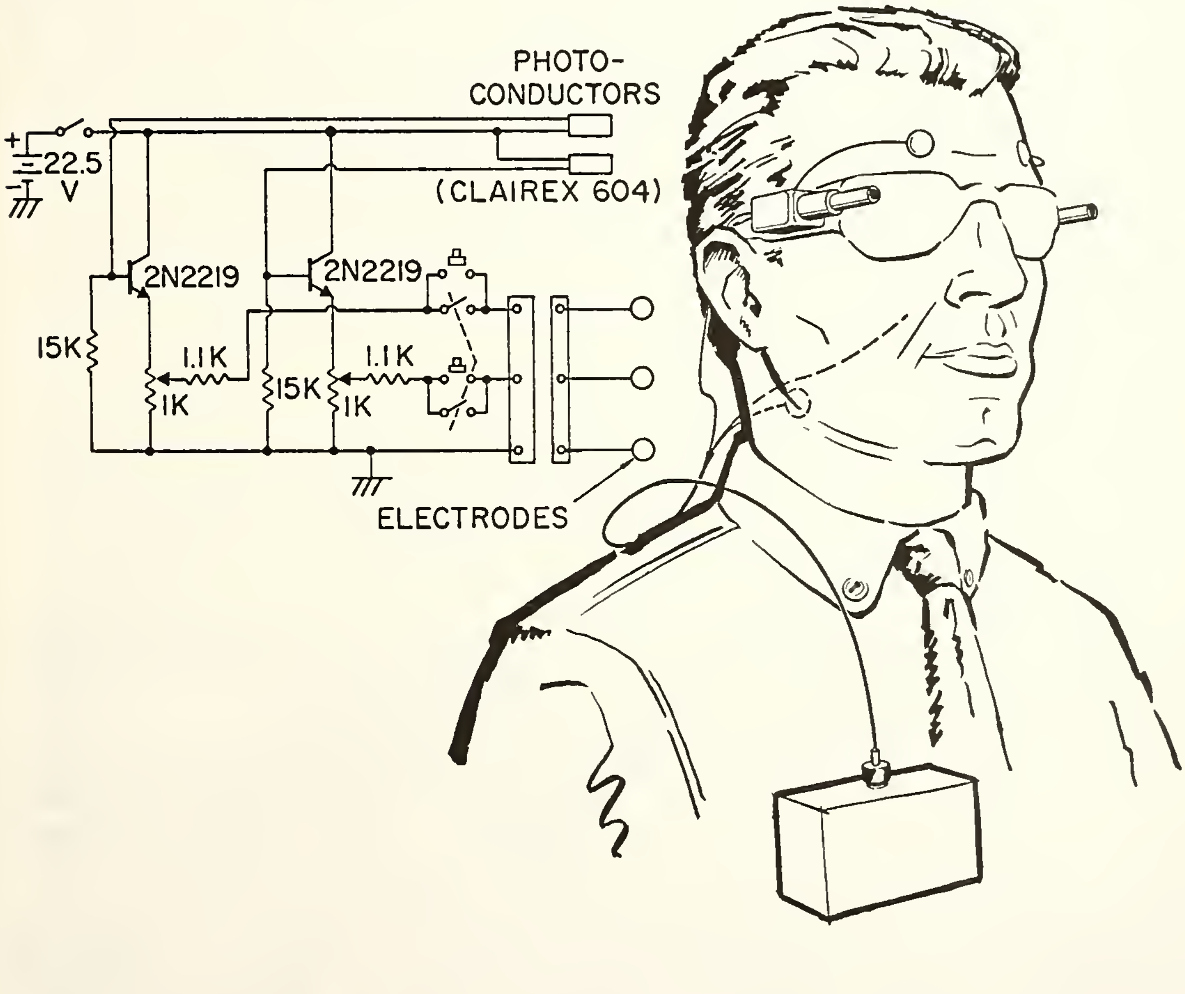

Figure 1. Schematic Diagram and Electrode Placement Locations for a Visual Prosthesis

Output is about 6 V for bright objects.

The intensity of the flash is a function of current (usually about 0.3 milliamps), rise time, repetition rate, past stimulation experience, concomitant auditory noise, and even time of day as the sensitivity of the eye to electrical stimulation has a circadian rhythm (20). Rise time dependency might be more an electrode counter-EMF phenomenon than a characteristic of phosphene generation, as may be optimum repetition rate. Theoretically, waveform should be important, particularly in color production; early experiments demonstrated that different colors could be elicited depending on whether the anode or the cathode was nearer the eye being stimulated. The spatial identification of the flash is a function of the location of electrode application on the forehead or face--for example, an electrode applied over the right temporal area gives an impression of a flash, usually a bluish-white crescent, a few meters above and to the right of the subject, and an electrode placed on the forehead midline will give a sensation of a flash in both eyes located centrally a few meters ahead of the subject. Experiments with multiple electrode systems using intensity and delay combinations have not been conducted.

A simple device weighing one kilogram was made (Figure 1) using two photodetectors mounted on ordinary glasses frames, and two independent amplifying systems, one connected to each photodetector with a common electrode to the neck. The system shown in schematic fashion (Figure 1) was designed to deliver 0 to 10 volts depending upon the luminosity of the light at which the sensor is "looking." The device has been used in the pulse mode wherein the experimental subject interrogates the environment either on the left, right, or center by manually depressing buttons and a flash is detected when the luminosity "seen" by the photodetectors changes. Electrode polarization and skin resistance problems are still troublesome. An automatic pulsing circuit with rise time (Figure 2) or current intensity dependent upon light luminosity "seen" by the photodetectors would probably be a better environment sensor. The use of an electromagnet induction coil and appropriate circuit might enable one to achieve similar results without the cumbersome electrodes.

Experiments are being conducted with the simple device of Figure 1 in order to ascertain whether phosphene generation is a practical means of transferring information about the environment to the visually impaired, the spacewalker, or the deep-sea diver. Most of the subjects have been children with retrolental fibroplasia, and the results indicate that a device as simple as that illustrated by Figure 1 would allow these children to navigate in areas where the light-dark contrast is great. Children having no memory of light as a sensation characterize the impulse as something new, describing it as a "bong" or "tap." Whether this device or a more sophisticated environmental sensor (1) can aid blind patients without eyeballs because a retina and nonatrophied optic nerve might be necessary is moot. Our experiments with enucleated patients have been inconclusive, and although the possibility of

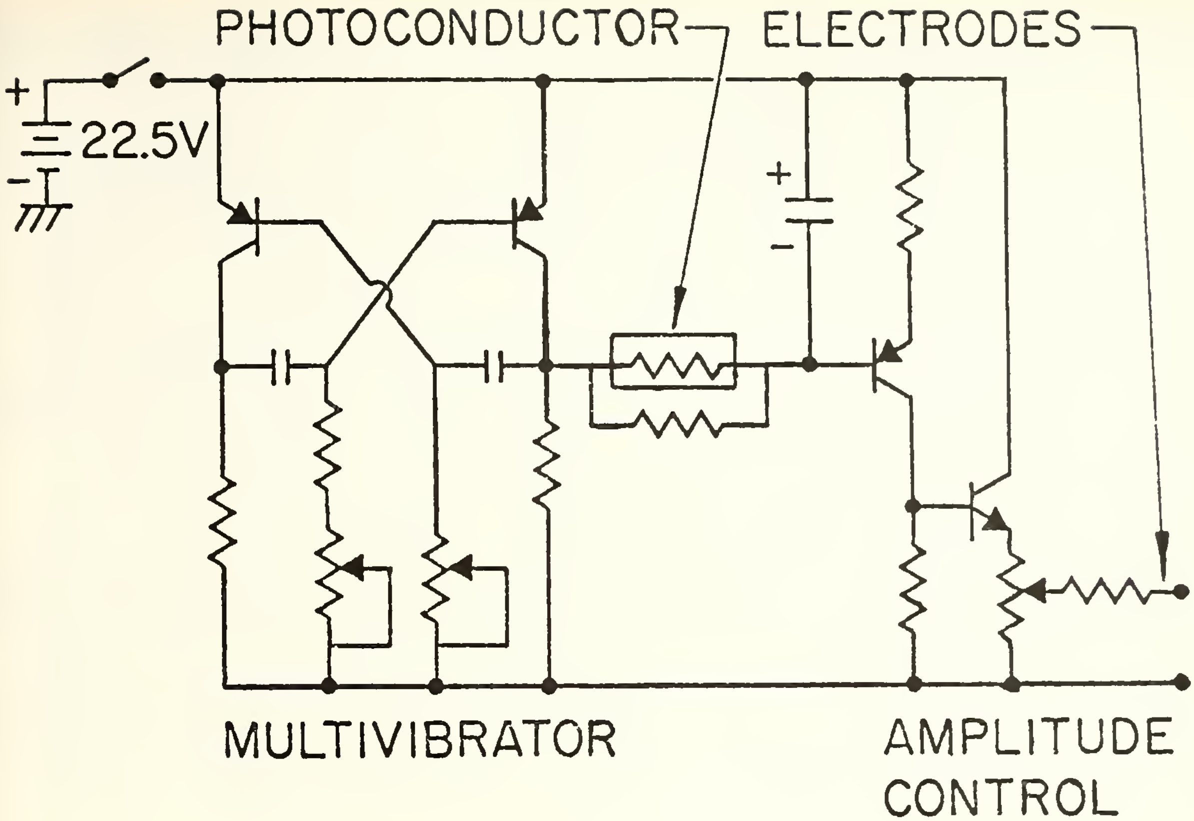

Figure 2. Schematic Diagram for a Circuit That Will Give Visual Flicker Sensation with Subjective Intensity Controlled by External Light Luminosity "Seen" by Photodetectors

a trigeminal to visual cortex pathway is remote, it should be subjected to further investigation. Children with severe visual impairment were apparently able to navigate better than usual using natural light following use of the device. This suggests that electrical stimulation of the defective retina might effect a lowering of the threshold to natural photic stimulation; however, navigation enhancement is often the case after a training session with other prosthetic devices.

Several aspects of this problem need much more work. The hypothesis is that color is a function of waveform and the relationships between flash intensity, voltage, and rise time (dv/dt) need further investigation. If these questions are resolved, pattern development might be implemented by an array of photodetectors connected to a multielectrode system on the forehead or eyeball (17). One of the most promising approaches is an electromagnetic coupling system between the environmental sensor and the brain. Using magnetic field fluctuations of about 1000 oersteds, one can induce the flash sensation either through the phosphene-retinal pathway or

some other mechanism not yet delineated. Caution should be exercised in experimenting with static fields over 80 oersteds; the depression of cellular respiration might be disastrous (21).

Whatever the mechanism or pathway, a device based on the concepts discussed here might provide a practical means of transferring information about the environment to the visual cortex without interfering with other sensory modalities. The development of a system using photodetectors or even infrared sensing devices, sonar, or Gunn Effect radar should not require a large federally supported effort (22), but more bioengineering and experimentation will be necessary before the blind can be offered a practical device. Further, a sophisticated training program for the user would necessarily be an integral part of the development of such an aid; otherwise the gadget, no matter how electronically compact and attractive or sound its physiological basis, would remain in the laboratory.

Results of our studies and the phosphene patterns studies using normal adults (23) suggest that subjective abstract light patterns can be controlled by waveform, repetition rate, electrode placement, and current. Thus, the information capacity of the phosphene mode might be much greater than is apparent on cursory examination. It remains to be seen whether the practical embodiment of electrical or electromagnetic stimulation of the visual apparatus can provide a more useful prosthesis than tactile and auditory feedback devices now being investigated (24).

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Reservations about whether induced phosphenes can transfer sufficient information to the blind are shared by the author.

COMPUTER SIMULATION OF MOBILITY AIDS: A FEASIBILITY STUDY*

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Abstract

We report the results of a feasibility study of a computer facility to simulate a wide class of potential mobility aids for the blind. The simulator will permit controlled experiments on blind Ss *to determine the characteristics of information about the environment that maximally enhances their navigational ability. This knowledge will furnish criteria to evaluate, for possible inclusion in future mobility devices, features of environmental detail extraction.*

Standard digital computer solutions to the fundamental subproblem, the simulation of a range-only, pencil-beam sensor, are presented. This mobility aid measures the distance to the closest object along a specified straight line path. We discuss in detail two different methods of environment representation, and several simulation techniques embodying these representations. In this development one sees trade-off properties among computation speed, storage capacity, calculation accuracy, and generality of the testing environment. We find that an 8,000-word memory is sufficient. If, however, we preserve reasonable standards in calculation accuracy and require that the environment be natural, then simulation on available digital computers fails by two orders of magnitude to achieve the desired 1,000 pencil-beam calculations per second.

Arguments are advanced for the use of an independent scanner/range finder coupled to a digital processor. We detail in functional terms one realization of the control circuitry for a single-channel or an optically multiplexed flying spot store and scanner. The multichannel system scans faster and requires less precise beam positioning, simpler control circuitry, more complex optics, and far greater quantities of optical and detector componentry than does the single-channel system.

In section 1 we develop a simulator philosophy that characterizes useful environmental detail as knowledge of the existence, location, and descriptive properties of significant environmental discontinuities. We present, in section 6, ideas on the extension of a range-only, pencil-beam simulator to a general purpose mobility aid simulator. The nature of experimenter-machine and S*-machine interaction in a simulation facility is*

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considered. We speculate on experimenter-subject interaction, the nature of the experimental testing program. Finally, recommendations for future research, chief among them the further study of and equipment development for a flying spot scanner system, are presented.

1. A COMPUTER SIMULATION FACILITY FOR MOBILITY AIDS RESEARCH

Mobility Aids for the Blind

A mobility aid provides a trained blind person with environmental information that facilitates his passage through both familiar and unfamiliar surroundings. The cane, the *seeing-eye* dog guide, and the human companion are mobility aids used commonly today. In the past two decades university and industrial research groups have begun to employ modern electronic and optical technology in the design of mobility aids for the blind.

We distinguish two aspects of a mobility aid: its purpose, or function, and the hardware realization that accomplishes the function. More specifically, we can characterize a mobility aid in terms of the information about the environment extracted by the device. Different structures may accomplish an identical function. For example, the knowledge of the existence of obstacles in the path of the blind man is the environmental information that may be extracted, in principle, by either an ultrasonic or an optical device.

We wish to isolate two questions corresponding to this dichotomy of function and structure: What information about the environment maximally increases a sightless person's mobility? How can we build a device that accomplishes this function, under the usual economic constraints of cost, size, and weight?

Our present interest is in the former problem, which involves a whole class of considerations about the "navigation" of the blind and the psychophysics of blindness. In particular, we want to investigate these questions without tackling the difficult instrumentation problems. A broad view of the structure of a research program suggests that we first ascertain which environmental details should be given the blind; knowing this, we then should attempt to build the requisite hardware.

Computer Simulation of Mobility Aids; Its Utilization in the Evaluation of Future Mobility Aids

The simulation power of the modern digital computer can, in principle, enable us to structure our research in this fashion. Experiments on sightless *S*s are conducted in a testing room filled with a carefully chosen set of "obstacles." Stored in the computer's memory is an environment description, containing at least the locations, shapes, and sizes of the

objects. *S* wanders through the room, either freely or with instructions to carry out a specific task. He carries a dummy mobility aid, a rod that defines a reference direction; its position and direction are monitored continually and sent to the computer. To simulate a given mobility aid, the computer's program calculates the information that would be extracted from the environment by the simulated sensor. For example, it may calculate the distance to the closest object in the direction of the rod. This information can then be relayed immediately (in "real time") to the blind *S*, and presented by means of the appropriate auditory, tactile, kinesthetic, or thermal displays.

We have thus isolated and preserved the function of the simulated mobility aid without any concern for the structure. What have we gained? A device is versatile if minor modifications in structure can result in major modifications in function. A digital computer simulation program should be more versatile than the corresponding hardware realization. The task of designing a cheap, lightweight mobility aid with even a very limited function is presently so difficult that one can not expect general-purpose structures. Unlike hardware, the simulation program should be amenable to unforeseen modifications and additions. In this report we advance arguments that tend to support this versatility hypothesis.

Environmental Information to Increase the Mobility of the Blind

To establish more specifically the grounds for employing computer simulation, let us look at the types of questions we hope to study with the facility. To convince ourselves that what would be maximally useful to a sightless person is not obvious, let us conjecture what should be the functions of future mobility aids.

Initially, we distinguish between two aspects of the environment, the objects above ground, which we denote "obstacles," and the ground, or terrain. What knowledge about the obstacles could improve a sightless man's mobility? The simplest question is that of the existence of any objects along a specified path or in a sector defined by a pencil (zero-angle) beam, a narrow-angle beam, or a wide-angle beam. Of interest are the distances to objects and the distances between objects, which specify the width of aperture through which the man can pass. It may be useful to know some of the object characteristics--for example, shape and size, with emphasis on such potential danger points as the height of steps, the length of protruding beams, and the sharpness of exposed edges. Details of texture and solidity may also be of interest. Doubtless of significance is the identification of moving objects and their speed.

What information about the terrain could be useful to the sightless? The most basic question is again one of existence, the existence of any terrain changes occurring along the man's presumed future path. This notion can be made more precise by specifying, for example, changes in the ground's inclination, step-ups or step-downs in the terrain, and changes in ground texture.

Unanswered Questions About the Nature of Useful Environmental Information: The Use of the Computer in Research on These Questions

We hypothesize that continual display of this information would increase the mobility of the blind. Yet these considerations have been of a highly general nature. They do suggest, however, a multitude of more specific, subtler questions: All types of environmental details discussed above cannot be simultaneously presented. How valuable is each one? Which are most important? How often should each type be given? Can they be effectively interleaved? How much control over their presentation should the user have? How quickly can he absorb the information? How much stress is engendered? What sensory modalities should be used? Can the information be multiplexed through simultaneous use of several sensory modalities? How does the artificially generated information interact with natural environmental clues? How can we preserve the best of both? Should the substance or method of communication depend upon the user's state of activity? We are faced with a wealth of deep, unanswered questions.

To be yet more specific, let us pose typical questions about a beam obstacle detector. What is best, a single beam or many beams? Should they be zero-angle, narrow-angle, or wide-angle? What should be the relative orientation of the beams? Should the number of beams, angles, and orientation be user-controlled or fixed? What should be the character of the output? In the multibeam case, how should multiple coincidences be treated?

The scope and profundity of these hardly-tapped questions demands a vast research effort. This effort in turn demands either a versatile set of mobility aid prototypes or a versatile general-purpose simulator. Our supposition is that it will be quicker and cheaper to design and develop the simulator rather than a large set of devices. In addition, the progress of research should not render the simulator obsolete. Therefore we undertake the design of a computer simulation facility.

Present Research in Mobility Aids Design

To further justify this effort, we must look more carefully at the state of the art and the promise for the future in the design and construction of mobility aids. There are today no mobility devices in appreciable use except, of course, the cane. At the June, 1962, International Congress on Technology and Blindness, in the panel on mobility and mobility devices, the following mobility aids were presented as in the design, prototype construction, or evaluation stage (2):

Kay of the University of Birmingham reported work on ultrasonic guidance systems, with pulsed and continuous wide-band frequency modulated signals emanating from a torch with an effective beam of about 10 degrees. A narrow angle beam of light

is used in one other obstacle detector. Still another device, an "electronic cane," possessing all the features of a primitive stick, also warns the users of step-downs in his path.

These are examples of "active" systems, which send out their own energy, sonic or electromagnetic, to the environment; in addition the following "passive" systems were introduced: Researchers from Poland discussed a multichannel visual-to-tactile transducer that reproduces, somewhere on the user's body, the outputs from a mosaic of photoelements, a crude "picture" of the environment. A "stereo-optical" edge detector that uses two mosaics of photosensitive elements was being constructed. An ambient light obstacle detector gives a positive output when a vibrating mirror brings into focus an object in the field of view. Finally, two straight line travel indicators were discussed.

An Interpretation of the State-of-the-Art in Mobility Aids Design: Its Implications for the Desirability of a Computer Simulation Facility

We have not in our research undertaken an exhaustive survey of mobility aids presently in construction, nor have we attempted to design versatile mobility aid prototypes. Yet it is clear that the design, construction, and debugging of any mobility aid, however limited in function, is a task severe in its man-hour demand. The difficulty increases as one attempts to incorporate more flexibility and versatility into the device.

Thus, truly general-purpose devices that are able to extract from the environment a significant number of the features discussed above are unlikely, at least in the near future. This statement requires a slight qualification. A particular mobility aid may extract some information (in the information theoretic sense) about many of the spatial and descriptive characteristics of the environment, but the nature of the output is intrinsically determined by the structure of the device. For our envisioned experimental program, this is undesirable. We wish independent access to any or all details of the environment. We do not deny the value of instrument-centered experimentation; we should like, however, independent controls of environment detail extraction.

Organization of the Computer Simulator

Even if one grants that today's and tomorrow's mobility aids do not serve the desired general-purpose function, we must still explain how the computer simulator will effect the desired versatility. To do this, we must first reiterate and reformulate our notions of the general types of environmental information useful to the sightless.

We distinguish obstacles from terrain, and in each case note that the fundamental question is one of existence, the existence of obstacles or terrain changes along a path or within a sector. The second set of questions is one of spatial description--the location of obstacles and their speed of movement, and

the location, direction, and steepness of terrain change. Finally, we seek more complete descriptions--shape, size, and texture of the obstacles, and texture of the terrain.

We can evoke another similar unifying structure which indicates one reasonable approach towards a computer simulation. To describe both obstacles and terrain, we first sweep the desired path or sector searching for the existence and for the location of significant discontinuities. The second step is a description of the object located by the first step. Thus, in principle, the computer simulator can accomplish all desired functions with a search procedure leading to establishment of existence and location, and with a table of obstacle and terrain descriptions, appropriately referenced by the object location. More specifically, the program can search for an object; upon finding one it can extract all environmental details about this object from a coded list stored in memory. In this report we concern ourselves chiefly with the more difficult search problem and indicate briefly how one might handle the description lists.

The Fundamental Problem: Simulation of a Range-Only, Pencil-Beam Sensor

Thus, to investigate the feasibility of a mobility aid simulator, we must consider how a computer can carry out a search procedure along a path or through a sector of a complicated environment. Yet beforehand we must tackle the problem of storage in a computer of a complicated environment description. We then assume a method of description and consider the problem of a range-only, pencil-beam (zero-angle) detector. Such a sensor provides the distance to the closest object along a specified straight line path. The simulator generally provides the coordinates of the object as well. We have at present found no good techniques to search a sector of the environment, and none that differ significantly from simple iteration of the pencil-beam algorithm. This strengthens our belief in the fundamental nature of the pencil-beam detector.

Here we state and explain our philosophy in the search for a simulator of the pencil-beam sensor. The goal is speed. The desired order of magnitude of speed may be seen by the following rough argument. It would be interesting to experiment with information transmission rates of the order of ten messages per second. Yet in a tenth of a second *S*'s arm may sweep out a large enough sector that the sensor would miss, for example, a post. To avoid such a situation, the computer can calculate at a higher rate. Finally, if we must iterate the pencil-beam calculation to form wider angle beams, this requires yet greater speed. Thus it is reasonable to demand 1,000 pencil-beam calculations per second.

A Preview of the Report

We shall find that this speed goal is an impossible task with today's digital computers, yet possible with the use of an auxiliary special-purpose store and scanner. We discuss in depth algorithms for digital simulation, however, to ascertain the nature of the calculation power-speed-memory trade-offs encountered. We shall see the severe compromises in speed, generality of the testing environment, and computation accuracy that must be made in order to simulate by standard digital computer a single pencil-beam, range-only sensor. Because we are unwilling to accept such compromises, the verdict of "too slow" must be applied to all the techniques considered. To obtain a better feel for the types of bookkeeping and the other problems that would arise, we shall consider how to set up on the TX-0 computer the simulation of a pencil-beam sensor in a small-scale, two-dimensional environment.

Next we discuss techniques involving standard digital processors coupled with special-purpose memory devices that also serve as scanners and range finders. Emphasized is the flying spot store and scanner; we outline in functional terms one possible design and recommend the development of control circuitry for either a single-channel or multichannel system so that one or the other may be used in the initial large-scale simulation project. We consider the extension of a range-only pencil simulator to a general-purpose simulator. There follows a discussion of experimenter-machine interaction (the master control program, subject-machine interaction), user control of the simulator and the output displays to the user, and the types of experiments to be run and data processing therefore required. Finally, we consider some other advantages and disadvantages of the simulator system; we summarize our conclusions, and indicate recommendations for future research.

2. "OBJECT-CENTERED" SIMULATION BY STANDARD DIGITAL COMPUTER OF A RANGE-ONLY, PENCIL-BEAM SENSOR

Computer Representation of the Testing Room Environment

<u>The Nature of the Testing Room.</u> The initial problem is to find a suitable computer representation, or method of storage, for the testing room environment. We must first consider the nature of the room to be represented.

The testing room should satisfy the following criterion: It should be natural, not artificial, in the sense that it be a good example of a "typical" environment that a blind person would encounter. Located in the room must be a good sampling of many of the natural hindrances to mobility--for example, terrain changes, step-ups, step-downs, obstacles on the ground, objects protruding from the walls, and doorways.

With respect to its effect on the choice of representation, the key description of the desired environment is one of complexity. We should require both complexity in the location of the objects and natural complexity in the structure of the objects themselves.

Keeping this in mind, we consider what choices of representation are open to us and what questions about representation we must answer. One obvious issue is that of a coordinate system. Given a coordinate system, one must choose a method of data storage. In this choice the criteria are the capacity requirements, the fidelity of the representation, and the more significant issue of the speed of the forthcoming extraction of data during a real-time experiment.

Choice of a Coordinate System. Unless there exists virtually perfect cylindrical or spherical symmetry in a problem, it is usually easier to use rectangular coordinates. A necessary condition for calculation ease with cylindrical or spherical coordinates is that the center remain fixed relative to the objects of interest. Consequently, it is impossible to use the man's position as the center of such a system, because as he moves, all objects must acquire new coordinates. There is insufficient time for the computer to recalculate coordinates after each movement of the subject. Yet in order to calculate the range from a particular point, that point is the only sensible choice for a center. We therefore choose rectangular coordinates and a rectangular shape for the testing room.

Methods of Data Representation and the Problem of Environment Complexity. There are two fundamentally different approaches to the problem of representation. The first method, which we denote "brute force" storage, is based on the principle that the space-filling property of any set of objects in three-space can be represented, with any desired accuracy, by splitting the space into a matrix of three-dimensional elements and labeling each element with a "1" or a "0" on the basis of the presence or absence of object material. In a rectangular coordinate system one would naturally use cubes or rectangular parallelepipeds as the elements.

The second method, which we denote "object-centered" storage, treats each object as an entity and stores a description of its location, shape, and size. For example, each object could be characterized by its bounding surfaces; this would uniquely describe its space-filling properties.

We now consider the notion of environment complexity, in particular, structural complexity, discussed above. Since the objects cannot all be rectangular solids or spheres, but must include staircases, tables, poles, and doorways, the approach of object-centered storage is severely complicated. If there are n objects, including the different sections of the terrain, the computer must store n complicated surface descriptions. The problem of storage is trivial, however, compared to that of real-time data extraction. Given a position and direction, the computer

must search for an intersection with each one of these n surfaces. (For the moment we ignore the possibility of a more sophisticated search procedure that reduces the number of objects to be checked; as we shall see, these heuristics save little computation time.) To develop some feeling for the difficulty of the problem, let us investigate the two elementary cases in which the surfaces are a section of a plane and a sphere.

"Object-Centered" Simulation Techniques

An Algorithm That Tests if a Ray Intersects One of a Set of Planar Sections. The problem is to find the most efficient algorithm that, given two points, the equations of a set of planes, and the boundaries of sections of the planes, ascertains whether the directed line defined by the two points intersects any of the planar sections. If there are several intersections, it identifies the one closest to the points.

The exploring ray defined by the two dummy sensor points (x_a, y_a, z_a) and (x_b, y_b, z_b) is described by the general equation of a straight line:

$$\frac{x - x_b}{x_b - x_a} = \frac{y - y_b}{y_b - y_a} = \frac{z - z_b}{z_b - z_a}$$

The general equation for a plane is $Rx + Sy + Tz = D$. The boundaries of the section are in general expressed as the equations of lines in three-space. This situation is so complex that we wish to restrict the boundaries to straight lines. Second, for simplicity, we assume that each plane is perpendicular to one of the axes, for example, the y-axis, and is therefore described by an equation of the form $y = y = y_c$. Finally, we assume that there is no degenerate case, that the exploring ray is not parallel to the $y = y_c$ plane. (This is implicit in the form of the ray's equations.)

Now the solution is a simple one because the boundaries are linear equations in x and z, $z = mx + n$. First the algorithm checks that the intersection is on the positive side of the ray, in front of the man rather than behind him. Then $y = y_c$ is inserted into the two equations of the exploring ray. Immediately are obtained the x_c and z_c of the intersection. Finally, the algorithm checks if the intersection is within the section, the boundaries of which are defined by a set of linear equations in x and z. The proper side of each boundary (again, ignoring degenerate cases) can be expressed as an inequality $z > mx + n$, or $z > mx + n$. If all such inequalities are satisfied, the point is a valid intersection. The method continues in this way, through every section of a plane, listing all valid intersections. Finally, in the event of several valid intersections, the one closest to the subject is identified by comparing the intersection coordinates with (x_b, y_b, z_b).

What effect would relaxing our assumptions have on the complexity of a computer program that carries out the above algorithm? The degenerate cases can be included with only minor conceptual but major bookkeeping additions to the program. If the conic sections are allowed as surface boundaries but the surfaces remain perpendicular to the axes, the boundary inequalities will be quadratic rather than linear. When this last, most restrictive condition of orthogonal surfaces is removed, more severe difficulties set in. The equation $Rx + Sy + Tz = D$ must be used to solve for the intersection. Each linear boundary is now represented by two equations; in general, three inequalities in two variables must be checked to ascertain if the intersection point lies on the correct side of the boundary. If one allows both nonorthogonal surfaces and nonlinear boundaries, the complexity is so extreme that in the light of our speed requirements it is nonsensical to consider it.

An Algorithm That Tests if a Ray Intersects One of a Set of Spheres. We have treated the simplest possible surface, that of a plane. Next we summarize the solution if the input data are two points and the equations of a set of spheres. The simplest approach requires the calculation of distances between three points, pairwise, and use of the law of cosines to obtain the angle between the line to the center of the sphere, from the user's position, and the exploring ray. A comparison between the radius of the sphere and the perpendicular distance from the center of the sphere to the ray determines whether there is an intersection. After each sphere is treated in turn, the closest intersection is identified by use of the coordinates.

Cylinders could be handled by a combination of the type of techniques used for planes and spheres. All these algorithms could be effected by one large program that initially references the algorithm corresponding to the type of object encountered. Since these methods will prove too slow even for simple surfaces, we do not consider techniques for objects of greater complexity.

Sophisticated Search Procedures. We are seeking search procedures more efficient than merely checking every object. One hopes that there exists an a priori ordering of a set of objects that would facilitate a partially alphabetic search, in which some description of each exploring ray limits the section of the alphabet to be searched. Unfortunately, we know of no such description that works for every exploring ray.

A second approach, a modification of the first one, requires finding a set of identifying characteristics, each of which would apply to some subset of exploring rays. Two examples are "remains in the upper half of the room" and "remains in a diagonal strip of an x foot width from corner 1 to corner 3 in the lower half of the room." These characteristics could be but need not be mutually exclusive. Tests for their presence may be given in a prescribed order, and a master scheduling program would attempt to minimize the maximum search time for all exploring rays.

To illustrate the difficulty in obtaining a sizeable speed increase with this approach, we discuss one specific set of identifying characteristics, a set invoking relatively simple geometric properties that are consequently easily identifiable. We divide the room, assumed to be cubical for simplicity, into a $k \times k \times k$ grid of large cubes, and assume the existence of an algorithm that identifies the cubes through which a particular ray passes. A ray may pass through a maximum of $(3k - 2)$ cubes. Stored in memory is a table that associates with each cube a list of surfaces, assumed to be planar sections, that lie in part within that cube. The search for intersections of the ray with the set of surfaces may be restricted to the subset of surfaces referenced by the subset of traversed cubes.

We shall derive an approximate upper bound to the percentage time saving that we may expect from such a scheme. We must temporarily assume that the surfaces are randomly distributed throughout the room. Each surface is located, on the average, in $q(k)$ of the cubes, where $q(k)$ should vary roughly as the square of k. We shall, however, include an algorithm that keeps a list of surfaces to be checked and therefore avoids duplication. Nevertheless, because of overlap from nonduplicating surfaces, we can assume that the maximum percentage of surfaces requiring checking is slightly greater than $(3k - 2)/k^3$. We therefore use, for simplicity, $(3/k^2)$ as the percentage of surfaces to be checked.

We must include an approximation to the time required to calculate the list of traversed cubes, to throw out duplications, and to throw out the duplications in the resulting list of surfaces. We estimate that this process should consume time on the order of that necessary to calculate intersections with $2k$ surfaces. Thus we obtain the fractional time consumption f by solving the equation

$$\left(\frac{3}{k^2}\right)S + 2k = [f(k, S)]S$$

for reasonable values of S, the number of surfaces, and k. To be specific, we choose $S = 75$, thereby obtaining the solutions:

k	$f(k,75)$
2	0.80
3	0.41
4	0.29
5	0.25
6	0.24
7	0.25
10	0.30

The minimum f decreases with S, as summarized in the following table:

S	$\min_k f(k,S) = f_m(S)$	$[f_m(S)]S$
100	0.20	20
75	0.24	18
50	0.32	16
25	0.51	13
10	0.93	9

Consequently, should we reduce the number of surfaces, the average number, $f_m S$, declines slower than linearly with S.

Finally, we must note that even if the surface distribution is as uniform as possible, because of the small number and the Diophantine constraints, there will exist some rays for which the number of surfaces to be checked will be above the average that we have calculated. More significant is the fact that an ideal uniform distribution would not permit a natural testing environment. Consequently, the expected deviations from uniformity result in a maximum value of f that exceeds the average. Our true concern is not with the average value, but with the maximum delay before the computer is ready with an output message for the subject. The user cannot be told: "Generally information will be given to you n times a second, but every once in a while you will have to wait twice or ten times as long." Our conclusion, therefore, is that the criterion of naturalness in the testing environment severely reduces the effectiveness of the sophisticated search procedures that we have considered.

Evaluation. The parallel line of thought for "brute force" storage is included, carried to greater depth, in the next section. Our conclusion is that this latter approach is preferable to the "object-centered" approach, except in cases of extreme and artificial environment simplicity.

The speediest brute force method, the "bullet procedure" coupled with three-dimensional array storage, requires, as we shall see in the next section, five additions, two multiplications, one word look-up, one bit look-up, and one test per iteration. As many as 400 iterations can be expected with a reasonable choice of room size, fineness of grid, and stepping length of the bullet. The simplest object-centered method, assuming planar surfaces orthogonal to the room axes and four linear boundaries per planar section, requires seven additions, seven multiplications, nine word look-ups, and five tests per planar section, plus another four tests to handle special cases. Unlike the multiplication in the brute force methods, which can be effected by a table look-up with 100 to 200 entries, the object-centered multiplication must undergo the slower process of calculation because there exist too many combinations to allow storage of a table. We can expect 50 to 100 surfaces in a typical room environment.

Consequently, we make the crude approximation that the calculation time for the simplest object-centered approach should approximate that for the simplest brute force approach. To obtain this result, however, we have had to place severe artificial restrictions on the character of the testing environment, restrictions which we are unwilling to accept. Nonlinear boundaries, such as circles and parabolas, on surfaces orthogonal to the room axes require on the order of two additions and one multiplication, per boundary, more than linear ones. Since this would likely be coincident with a number of boundaries that is less than four, we can allow such nonlinearities with little effect on calculation time.

The assumption of surfaces orthogonal to the room axes is damaging to our proposed experimental program, for it eliminates the possibility of such natural occurrences as inclined paths, crooked walls, nonorthogonal protruding objects, and ajar doors. If we relax the assumption, and there are four straight line boundaries, the solution requires approximately 27 multiplications, 21 additions, 14 tests, and 20 word look-ups per planar surface. Thus by an increase in computation time on the order of fourfold we allow all planar sections except those nonorthogonal to the walls that have nonlinear boundaries. Finally, the environment is artificial in that all objects of complex geometry are excluded.

We note that the algorithm to check if the ray intersects one of a set of spheres requires approximately ten squaring operations, three square root operations, two multiplications, and one test per sphere. Since one spherical object is surrounded by one sphere only, while a rectangular solid is covered by six planar sections, use of spherical objects would allow speedier calculations. Yet the character of our result is unchanged, because more of the objects in a natural environment must be covered with planar or planelike surfaces than with spheres.

We shall see in the next section that even the brute force bullet procedure fails by two orders of magnitude to provide the requisite speed. This fact alone forces rejection of both the brute force methods and the object-centered methods which, as we have seen, are in general more time-consuming than the bullet procedure. We shall eventually recommend techniques that utilize a standard digital computer coupled with auxiliary special-purpose storage and scanning devices. If, however, new technological advances or availability of only a standard digital computer should facilitate or necessitate simulation with a standard digital computer, then the considerations in this section should provide the insight to answer such questions as: "For the specific digital computer at hand, how artificial need be the environment in order that an object-centered approach furnish the quickest method of calculation?"

The approach to such a question hinges upon the functional dependence of the storage capacity C and the calculation time T upon parameters of the room environment. In particular, we consider the volume V of the testing room, the number S of object

surfaces, a measure A of the calculation accuracy, and a measure G of the object geometry. Since a typical planar section is characterized by ten to fifteen surface and boundary parameters, 50 to 100 such sections are easily stored in a typical 4000-word or 8000-word memory. The speed, however, is a serious problem; we have seen that T is not directly a function of V, but is proportional to S, and depends in a complicated way upon A and G.

Given perfectly accurate storage, sloppy calculation of intersections appears to save little time. Inaccuracy through simpler computer representations of surface descriptions, however, is of value. Yet rather than introduce this distortion, the same result is achieved by a true simplification of the object geometry. Although one must solve anew each different surface geometry, the included examples of planar sections are the simplest, the most fundamental, and are illustrative of the general approach. We have seen that relaxing the assumption of planes orthogonal to the axes multiplies T by a factor on the order of four. In principle such functional dependence upon object geometry may be exploited; yet with present technology this is of academic interest only, because the simulation of even the simplest case requires too much calculation time.

3. THE "BRUTE FORCE" SIMULATION OF A RANGE-ONLY, PENCIL-BEAM SENSOR WITH A STANDARD DIGITAL COMPUTER

In this section we develop algorithms with which a standard digital computer transforms an input of a "brute force" description of the testing room environment and the coordinates of two points on the subject's dummy sensor into an output of the distance, from one of the points, to the closest object along the straight line defined by the points. By standard digital computer we include core storage, magnetic drum, magnetic tape, and disk file storage, but exclude the flying spot scanner and storage tube. "Brute force" storage, defined previously, divides the room into a multitude of small elements, each labeled with a "0" or a "1" according to the presence or absence of object material. Any desired approximation fidelity may be obtained by varying the fineness of the three-dimensional grid. The walls of the room are stored as an object, with the consequence that there will always be an intersection. If desired, a special output signal could indicate that the wall is the closest object.

Resolution

Initially we consider the question of the envisioned size of the testing room, the desired resolution, and the resulting total storage capacity required. Although it is difficult, before experimentation, to judge the minimum size room that would be experimentally useful, we conjecture that 400 square feet should suffice for most purposes. Coupled with six feet of height, this necessitates a minimum of 2,400 cubic feet of volume.

The resolution is limited by the accuracy of the monitoring system that tracks the positions of the two points on the user's rod. The monitoring system, discussed in the next section, is expected to provide an accuracy of better than ±1/8-in. random error and ±1-in. systematic error. The systematic error should be almost identical for the two points. Thus each coordinate of the single point chosen as the measurement reference may be in error by approximately 1 in. The direction of the line defined by the two points, however, will not be affected by the systematic error.

The distance between the two points on the dummy sensor will be approximately 1-1/2 ft. Thus 1/8-in. random error in each coordinate of one of the points, with the other point held fixed, results in a 0.2-in. error in the distance from the true point and thus a 4-in. error across the diagonal of a 20' × 20' × 6' room. A 1/8-in. error of opposite sign in the coordinates of the two points approximately doubles the above error. We recall, however, that we are considering the worst possible case, and that the accuracy of a real mobility aid would decrease with increasing distance from the user.

Because the subject moves throughout the room, the fineness of the storage grid must be identical for the entire room. Therefore, unlike a physical device, the calculation resolution cannot be a function of distance. For objects near to the user, a resolution of 1 in. or 2 in. is desirable for our experiments. In the proximity of the subject such a resolution is not inconsistent with the above accuracy calculations. If 2-in. cubes are chosen as the elements, approximately 500,000 bits of storage capacity are required. For 1-in. cubes, 4,000,000 bits, and, for 3-in. cubes, 150,000 bits are needed. We shall see that the requisite number of bits of storage capacity can be varied through the use of different brute force coding schemes.

The simulation procedure consists of three distinct yet interrelated parts: an accurate, fast three-dimensional ray-tracing algorithm, a method of coding that provides the best trade-off between ease of access and storage capacity, and the method of access from the point calculated by the ray-tracer to the appropriate locations in storage, which we denote "data extraction." We initially consider the design of a ray-tracing algorithm, working first in two dimensions and then extending the results to three-space.

Ray-Tracing Algorithms

Two-Dimensional Ray Tracers. The problem is to design an efficient algorithm that, given a square room divided by a matrix of square elements, and two points, determines the coordinates of the elements that are intersected by an "exploring ray," a straight line through the two points.

We discuss below four different approaches, two which we term "microscopic" and two which we term "macroscopic." The two

microscopic algorithms track the line stepwise across the grid, determining coordinates of the elements while "passing through" them. Solution 1, the "bullet" procedure, increments the current x- and y-values by constant amounts to obtain the new x- and y-values. Unfortunately, the larger the step, the less accurate the calculation, because this algorithm misses corners. Solution 2, precise but much slower than Solution 1, calculates, given the point of entrance and direction of entry into each square, the point of emergence of the line from that element, and thus identifies the following square.

The two macroscopic algorithms determine a series of coordinates or pairs of coordinates from which a list of all the traversed squares may be calculated. Solution 3 calculates a list of x-coordinates that correspond to intersections with the lines $y = d$, $y = 2d$, . . . , $y = nd$ (d is the width of a square element; the matrix is $n \times n$). From this list it associates the correct x-value(s) with each y-value, thus forming the desired coordinate pairs. Solution 4 determines the point of emergence of the ray from the square matrix that corresponds to the room, and then subdivides each part of the intervening distance by two until every intersected square is represented by one of the resulting coordinate pairs. Both algorithms are perfectly accurate, but slower than the bullet procedure.

Solution 1

We assume, in all four solutions, an $n \times n$ square array, with coordinates labeled 1, 2, . . . , n (in units of d), and two input points (x_a, y_a) and (x_b, y_b), located on the dummy sensor. The slope m is defined to be $(y_b - y_a)(x_b - x_a)$. The flow chart of Solution 1, the bullet procedure, is shown on the next page.

The examination of location (x_k, y_k) for the presence of a 1, although not a part of the ray-tracing algorithm, is included to specify the complete search procedure. The ray-tracing algorithm itself requires only three programming steps (load, add, and store) per dimension per iteration.

Solution 2

Solution 2 is the procedure that traces the line through each individual square.

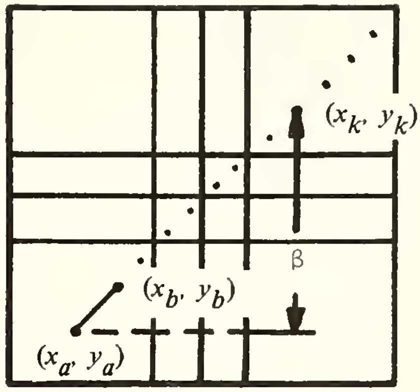
At all choice points where we have discontinued the flow chart along one branch, we have omitted for simplicity sections of the program similar to those included in the flow chart. We have omitted special cases such as $\beta = 90°$ or $m = 0$, which can be treated trivially with additional bookkeeping. We have left unexpanded the formation of (x_1, y_1), the ray's first intersection with the matrix, because it occurs once only and not in a loop.

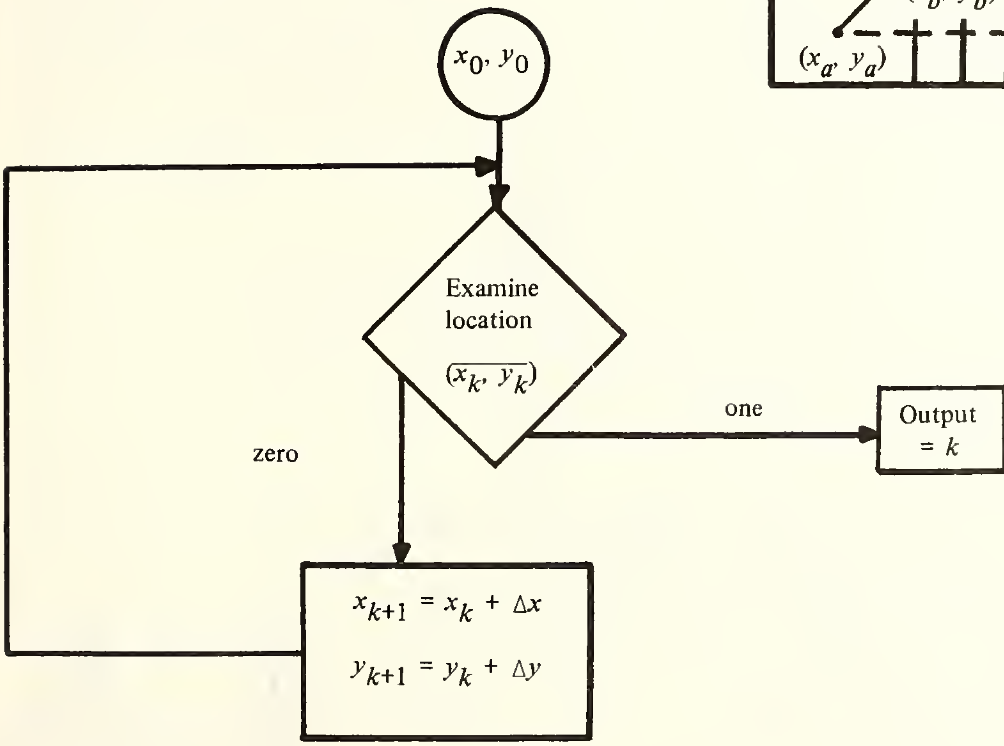
Let $(x_0, y_0) \equiv (x_b, y_b)$

$\left(\frac{\Delta x}{\Delta y}\right)$ is proportional to $\left(\frac{x_b - x_a}{y_b - y_a}\right)$

Notation: $\underline{q} \equiv$ integer part of q

$\overline{q} \equiv \underline{q} + 1$



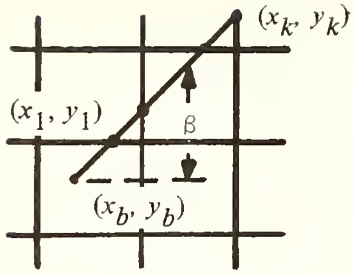


Solution 1

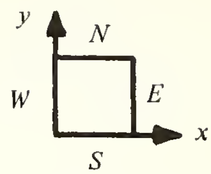
Solution 3

Solution 3 is the first macroscopic algorithm.

For the three quadrants ($90° \leq \beta \leq 360°$) not considered because the flow chart is abandoned at the choice points, the algorithm is trivially different from that included in the chart. Special cases are likewise easily handled. In Solution 3, unlike Solution 2, the initial transient is expanded in the flow chart, because its treatment is almost identical to the iteration steps.



The sides of a typical square:



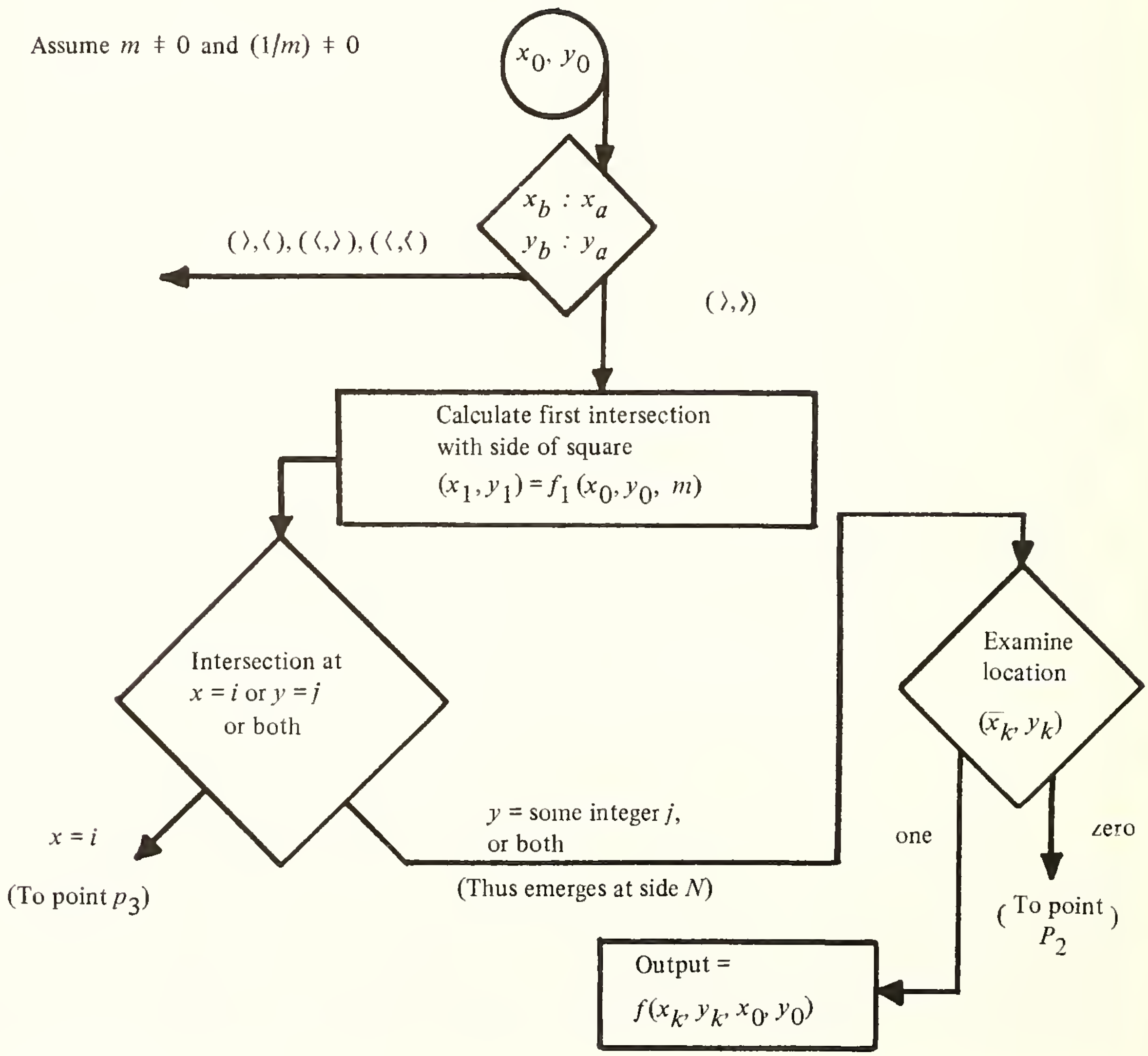
Notation: $\underline{q} \equiv$ integer part of q

$\bar{q} \equiv \underline{q} + 1$

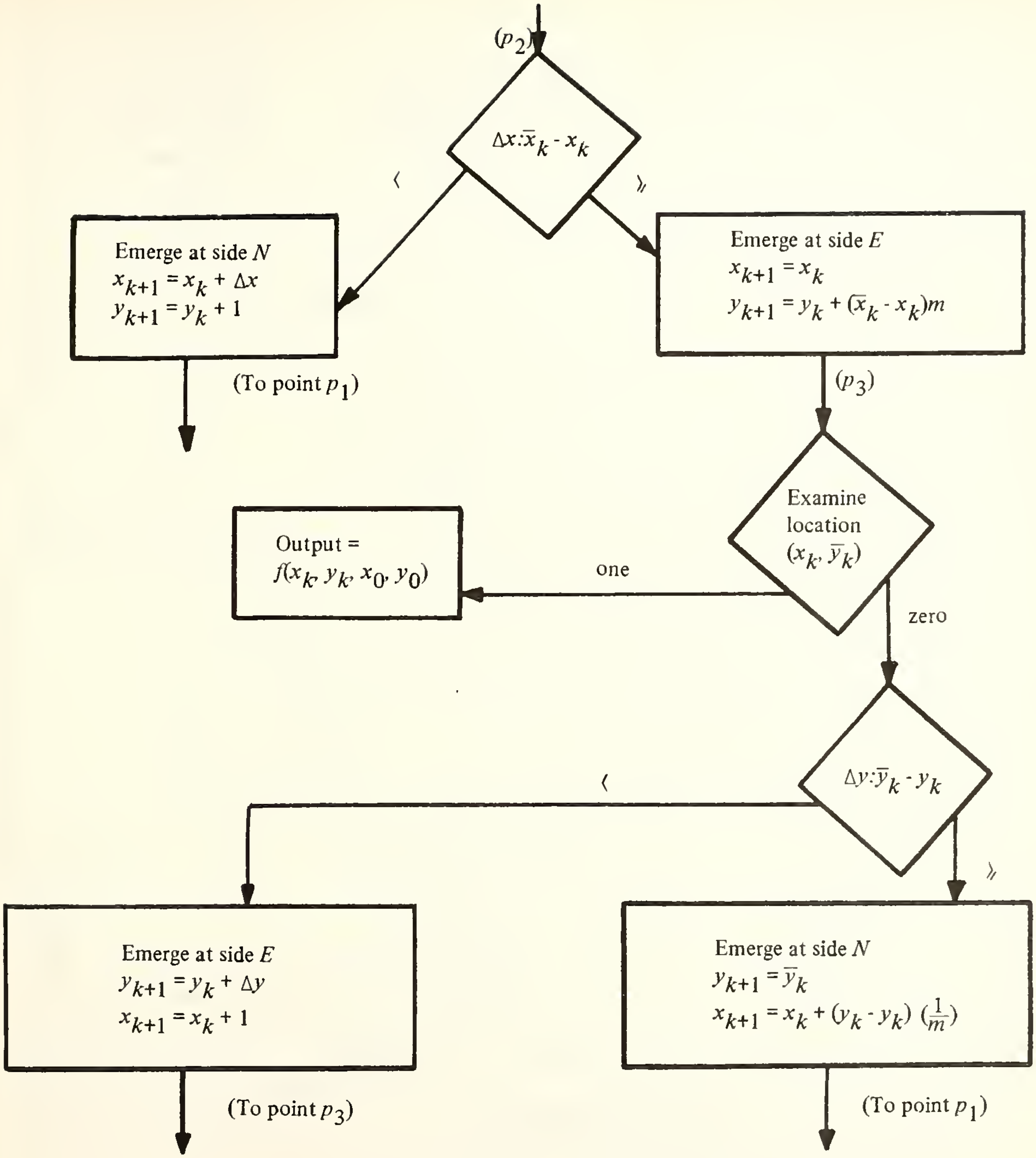
Assume $m \neq 0$ and $(1/m) \neq 0$

Define $\Delta x \equiv (\frac{1}{m})$, $\Delta y \equiv m$

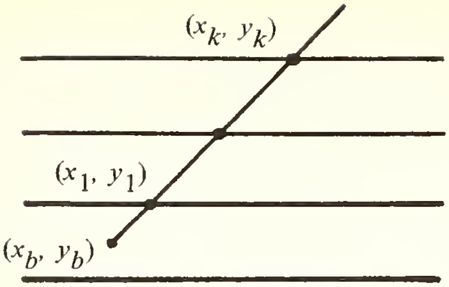
Let $(x_0, y_0) \equiv (x_b, y_b)$



Solution 2

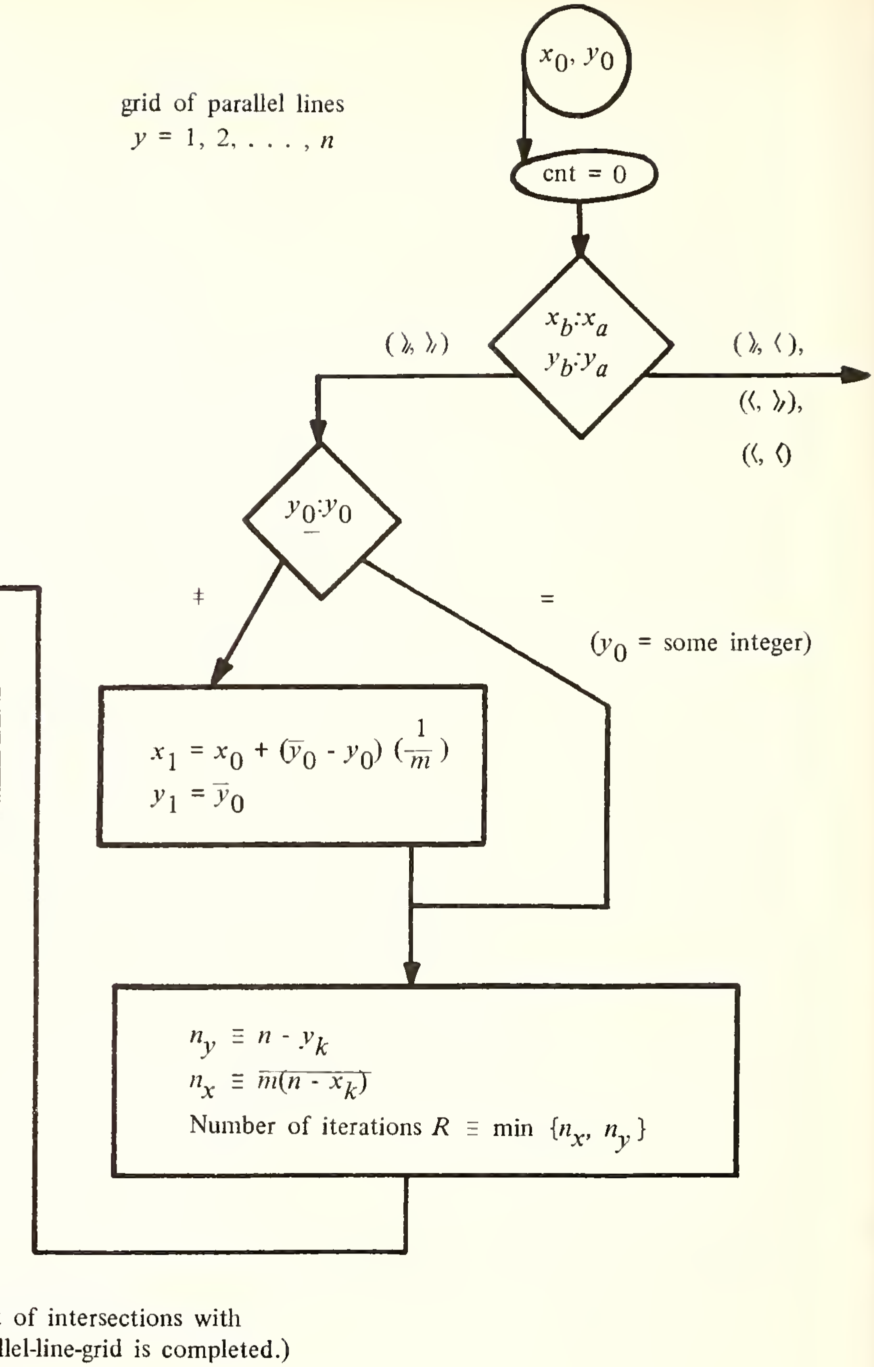


Solution 2 (Continued)



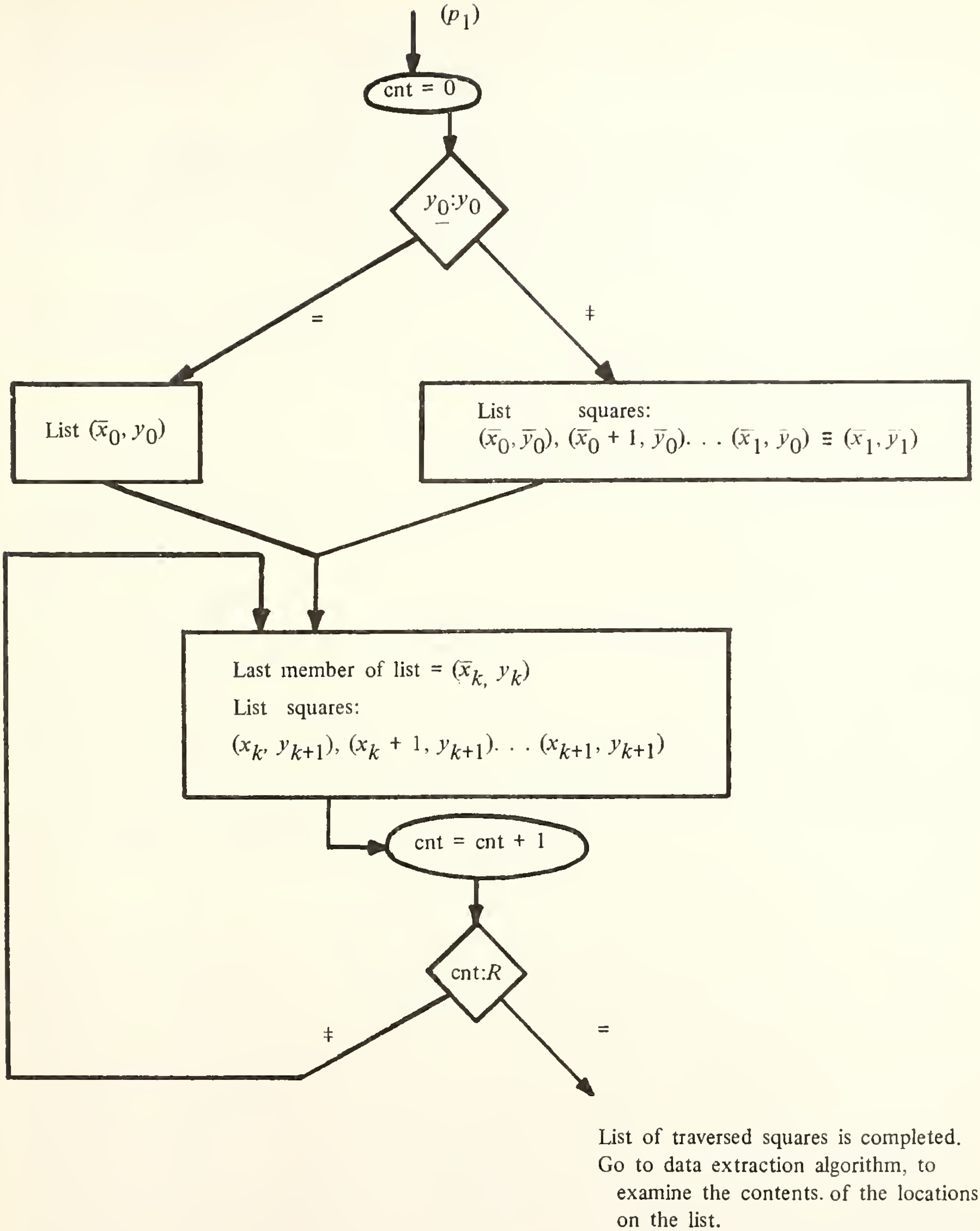
grid of parallel lines
$y = 1, 2, \ldots, n$

Notation: $\underline{q} \equiv$ integer part of q
$\overline{q} \equiv \underline{q} + 1$
Let $(x_0, y_0) \equiv (x_b, y_b)$



(List of intersections with parallel-line-grid is completed.)

Solution 3



Solution 3 (Continued)

Solution 4

The final flow chart represents Solution 4.

The other three quadrants are handled by almost identical algorithms; again the special cases are trivial. Unlike Solutions 2 and 3, there is no initial transient.

Extension of the Algorithms to Three Dimensions. To extend the bullet procedure to three dimensions, increment z by Δz, exactly as the x- and y-dimensions are handled.

The extension of Solution 3 is more difficult. We assume an $n \times n \times n_v$ array, with cubes labeled

$$(x, y, z), \ 1 \leq x \leq n, \ 1 \leq y \leq n, \ 1 \leq z \leq n_v,$$

plus two input points (x_a, y_z, z_a) and (x_b, y_b, z_b). We define

$$m_v = (z_b - z_a)/(x_b - x_a)$$

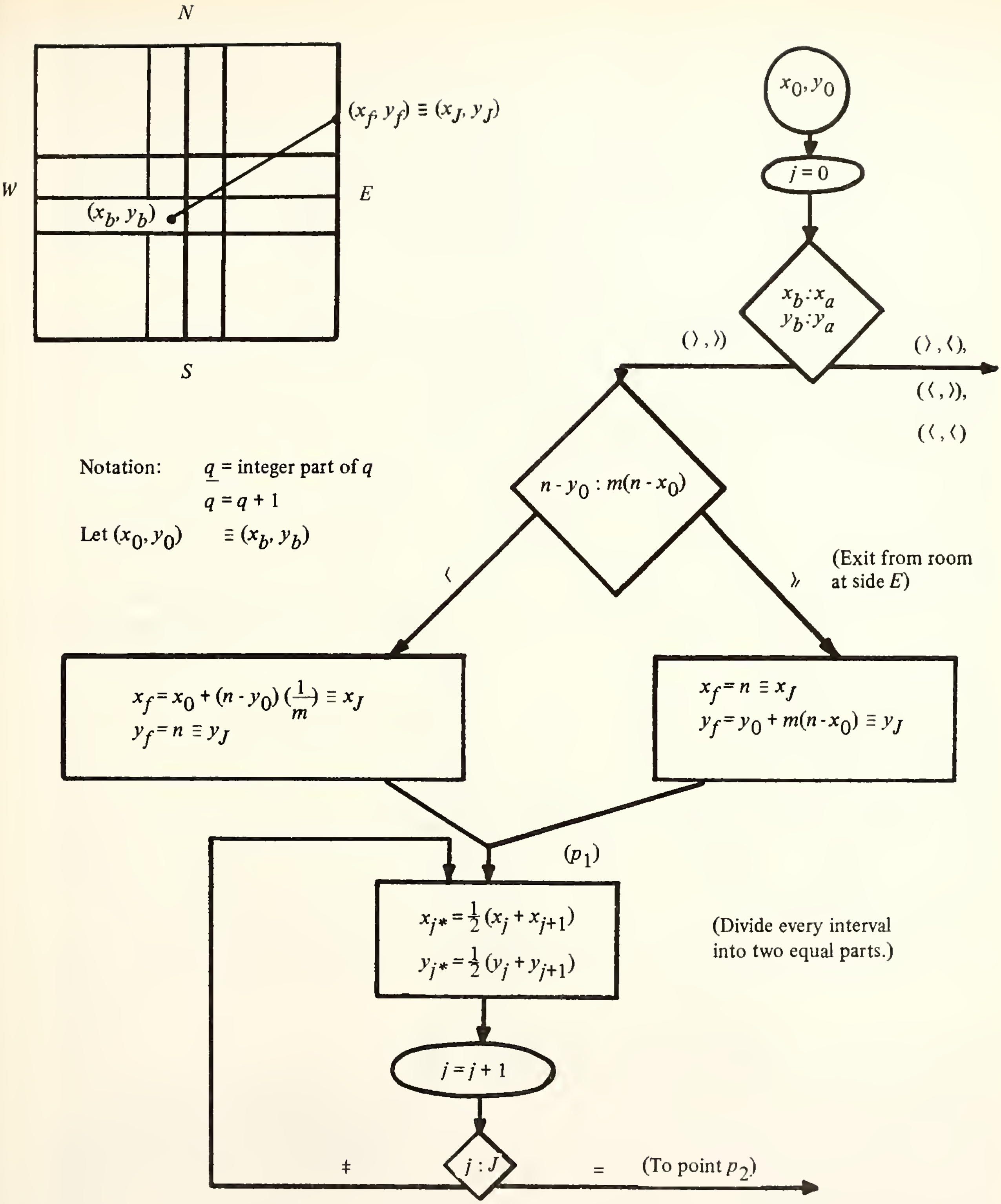
and

$$m_h = (y_b - y_a)/(x_b - x_a),$$

and assume for simplicity that $x_b \geq x_a$, $y_b \geq y_z$, and $z_b \geq z_a$. The methods for the seven other cases differ trivially from this method.

The first step of the three-dimensional algorithm is the application of the 2D procedure to the (x, y) projection of the ray, resulting in a list of x-coordinates which we label $_hx_i$. In similar manner is formed a list of the x-coordinates corresponding to integer-valued z. One can think of this list, its members labeled $_vx_i$, as the x-values corresponding to the emergence of the ray from one z-layer into the next higher z-layer. Finally, the algorithm associates with each (x, y) pair one or more z-values depending upon whether or not the ray emerges from one z-layer to the next or even succeeding z-layers while in that particular (x, y) square. This can be done easily through a comparison of the $_vx_i$ list with the $_hx_i$ list.

The three-dimensional extension of Solution 4 begins with a calculation of the (x, y, z) coordinate of the ray's point of emergence from the room, followed by successive subdivisions into two parts of the portions of the intervening distance. In the 2D solution, one checking algorithm is needed to insure that no intersected squares are missed. The algorithm calculates the difference between coordinates of the successive square elements on the list. If both differences are 0, or one coordinate difference is 0 and the other is 1, the subdivision is fine enough; if either difference is 2 or more, the subdivision is too coarse. If both differences are 1, the algorithm checks whether or not the line passes through the common corner of the two squares. If it does so, the subdivision is fine enough; if it does not, a square has been missed and the subdivision is yet too coarse. The 3D case requires a slightly more complex version of this procedure. The subdivision is fine enough if all coordinate

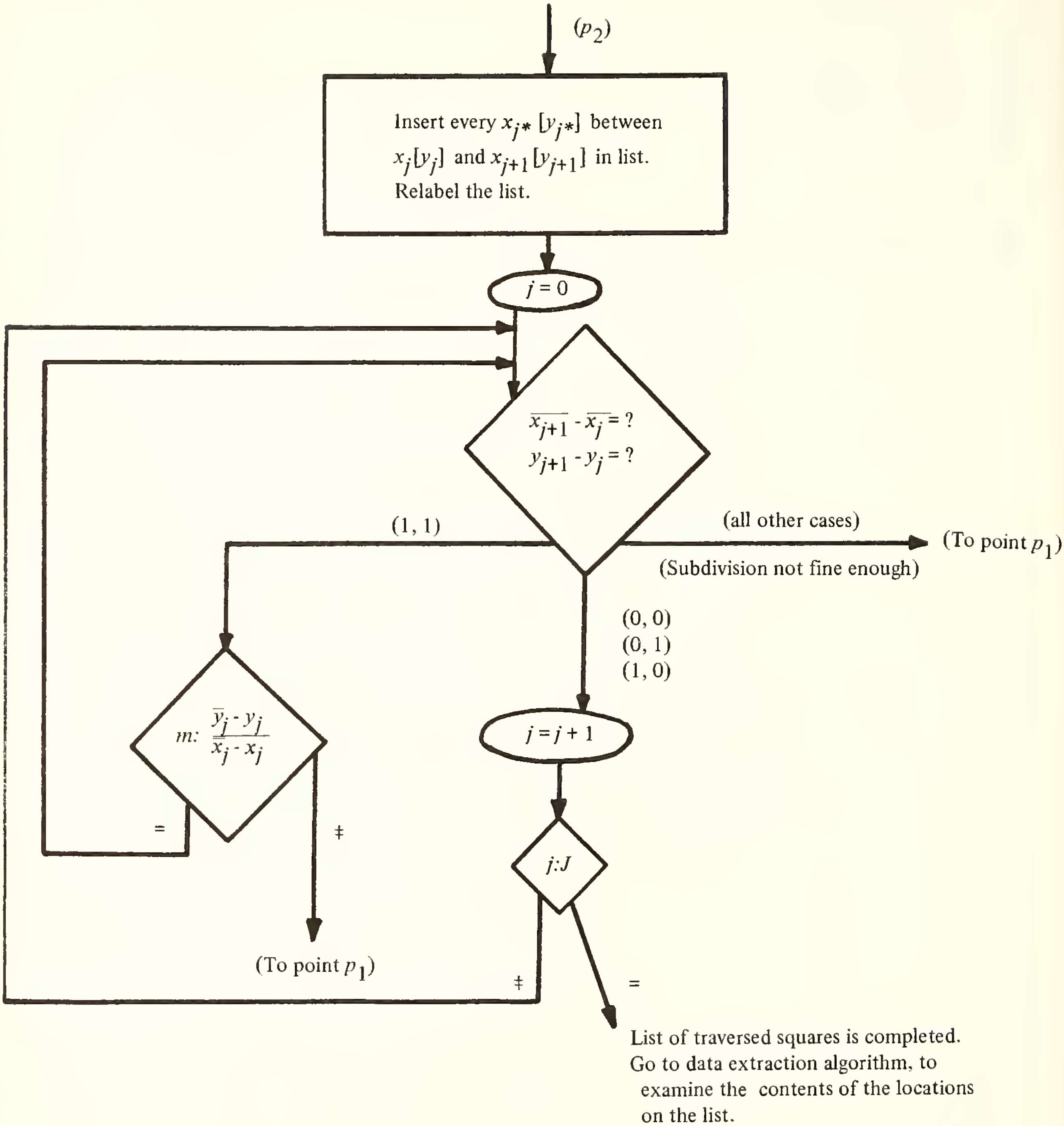


Notation: $\underline{q}$ = integer part of q

$q = q + 1$

Let $(x_0, y_0) \equiv (x_b, y_b)$

Solution 4



Solution 4 (Continued)

differences are 0 or if one is 1 and the other two are 0; it is too coarse if one or more of the differences exceeds 2; finally, if two or three of the differences equal 1, the algorithm must check for passage through the corner of a cube.

The extension of Solution 2 to three dimensions is most difficult of all, for it requires tracking the ray in three dimensions through every entrance and exit in a matrix of elemental cubes. The bookkeeping is so complex that it renders Solution 2 significantly slower than Solutions 3 and 4. We therefore omit details of the 3D extension

Evaluation of the Algorithms. To begin a comparison of the three-dimensional versions of Solutions 1, 3, and 4, we note that Solution 1 requires three additions per iteration. In the section on Evaluation of this chapter we shall suggest that the maximum number of iterations be on the order of seven times the number of elements n along a horizontal dimension. The 2D version of Solution 3 requires on the order of n additions, n truncations to integer-valued coordinates (that is, integer multiples of d), $2n$ additions of one, and $2n$ comparisons. In addition, regardless if operations of each kind are performed in sequence or are instead interleaved, the bookkeeping will be difficult for a computer with only one index register. The extension of three dimensions is essentially two of the 2D algorithms interwoven by complicated bookkeeping that emerges with a list of coordinate triplets. We estimate that Solution 3 should take on the order of one and one half to two times as long as Solution 1.

In some cases Solution 4 attains good accuracy only by subdividing the intervals into the finest subdivisions possible with the length of numerical representation employed in the program. In fact, it is very similar to the bullet procedure, with an algorithm to test if the subdivision is fine enough rather than a fixed subdivision set by a constant stepping length. Therefore, even if the subdivision is restricted to be no finer than that chosen for a bullet procedure, Solution 4 is slower due to the more complex bookkeeping employed.

Looking ahead, we note that we shall find that even Solution 1 is too slow for our purposes. We therefore choose not to undertake further detailed analyses and comparisons of these procedures.

Methods of Storage and Data Extraction Algorithms

The simulator consists of a ray-tracing algorithm, a method of storage, and a data extraction algorithm that locates the appropriate bits in memory when given the output coordinates from the ray-tracer. We therefore proceed to consider the latter two topics. Initially we distinguish between two fundamentally different methods of storage, array coding and run-length coding, and then discuss several schemes embodying one or both of these methods.

Array coding reserves a block of words with a bit total that equals the number of elements in the room matrix. A correspondence between bits of storage and room elements is established by a one-to-one mapping that is chosen to simplify the data extraction formula. We shall consider a single three-dimensional array and a two-stage process that stores one fine grain array description within a coarse grain description. We also discuss storage in three two-dimensional projections of the room environment, with appropriate corrections for distortions introduced by this mapping. (No inverse mapping can, from the three projections alone, reproduce the original three-dimensional structure.)

Assuming an ordering of the elements, run-length coding calculates some measure of the beginning and end of every string of filled elements, those containing ones. By storing these measures in a form from which the blocks may be identified, it uniquely specifies the contents of every element. Run-length coding is advantageous only if the density of 1s is low and the 1s appear in clumps rather than scatter individually.

After considering purely run-length methods, we discuss mixed array and run-length schemes, for example, array coding of the (x, y) information and run-length coding of the z-data. Finally, we consider an analogous scheme using an array code for both the (x, y) and z-data. This approach requires less storage capacity than a pure 3D array because it contains vertical list information only when there is at least a single one in that vertical column.

Data Extraction from a Three-Dimensional Array Code. The simplest case is pure array coding, in which we reserve one bit in storage for every room element. From our previous calculations, we require on the order of 500,000 bits, or 28,000 words of 18 bits per word, of storage capacity. A decrease in the size of the experimental testing room or an increase in the grid size, of course, reduces this figure.

How would one order such an array to facilitate ease of extraction of a particular bit? Our simplest solution is the following: Assume that the room array is $n_x \times n_y \times n_z$, and that the element coordinates take on values

$$1 \leq x \leq n_x, \ 1 \leq y \leq n_y, \ 1 \leq z \leq n_z.$$

Then each element is uniquely identified by the formula

$$\# = x + (n_x)(y - 1) + (n_x)(n_y)(z - 1).$$

Each identification number is then assigned a unique position in the storage array by the formula: Word location = integral part of $(\#/q)$. Bit location = $(\#)$ modulo q, where q is the word length in memory. Similar formulas can be applied in the case of signed coordinate values.

Must the data for such an array be in core storage? The answer is an emphatic yes. An article in the *Proceedings* of the Fall, 1963, Joint Computer Conference claims that the minimum average access time of present magnetic tape units, magnetic drums, and magnetic disk files, is the 15 milliseconds that can be obtained with a drum (3). Because our storage requirements are one to two orders of magnitude smaller than the figures he considers, we could expect comparably faster access times with properly constructed devices. However, we may have to look up 250 bits in a single range calculation. For any ordering of the data, there exist some exploring rays for which the search will require a traversal of the entire used memory with 250 stops to extract the appropriate bits. Between each look-up, of course, are calculations. Further work could be done to develop techniques that reduce access times by interweaving the ray-tracing calculations with estimates of the desired future location of, for example, a magnetic tape, and thereby determining positioning instructions for the tape unit. Such techniques, however, may consume as much computation time as they save in search time. At any rate, there is no doubt that data extraction from such memories is slower than from magnetic cores, which is, as we shall see, itself too slow.

Two-Level Array Storage. Having established that, for a pure array code, all data should ideally be in core storage, we nonetheless discuss the implications of a two-level or multilevel procedure that uses auxiliary storage efficiently. To be specific, let us consider the example of two levels of resolution, 1 ft and the eventual 2 in. The 2-in. description is identical to that used in the single level array code. The 1-ft description is obtained by coalescing the 216 small cubes inside each large cube according to the rule that, if and only if there exists a 1 in any of the small cubes, a 1 should be placed in the large cube. This coarse resolution array is stored in core memory. Corresponding to each coarse element a block of 216 bits in auxiliary storage contains the corresponding fine resolution data. The algorithm traces the ray through the coarse grid, and, for each intersection, brings the fine-grained data into core storage and traces the ray through it. An intersection with a large element "1" does not guarantee an intersection with any enclosed small element "1s." We note that the use of more than two levels is clearly disadvantageous.

Obviously this procedure solves the problem of a lack of magnetic core storage capacity. The ray-tracer must calculate to the resolution of the fine-grained grid; in fact, we recommended that it calculate to the higher accuracy immediately and "throw away" the superfluous places in dealing with the coarser elements. To minimize futile searches into the fine structure, the coarse grid should approximate the fine grid as closely as possible within the memory limitations. In an 8,000-word, 18 bit-per-word memory, 1,000,000 bits may be stored by a two-level

system in which the coarse grid is twice as big as the fine grid, in which to each coarse element in core storage there corresponds eight fine elements in auxiliary storage. Let the ratio of grid sizes be R, equal to two in the above example. To obtain the coarse coordinate values, divide by R the original coordinates and take the integral parts of the quotients; the fine coordinates are the original coordinates modulo R.

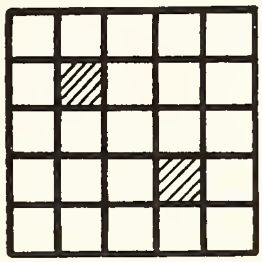
One apparent advantage of the two-stage system is that it appears to require a lesser number of iterations of the algorithm. We suspect that this gain is illusory, because there will always be an additional delay due to auxiliary memory searches, data transfer, and data extraction from the fine-grained structure. More detrimental is the fact that sometimes the combination of room environment and exploring ray will cause many "false alarms," intersections with filled coarse elements that do not result in intersections with filled fine elements. As a result, this calculation time will considerably exceed that of the single level procedure. For this reason we must discard the method, although we include one further observation. It is obvious that the success of this scheme hinges critically upon the choice of an auxiliary storage device with the shortest possible access time. New technological developments might sufficiently reduce the access time of some high-capacity storage medium so that this method could compare favorably with a single-level procedure in which all the data are in magnetic cores. We note that because the fine data are organized in blocks, the data transfer rates would be the maximum attainable for the auxiliary storage device.

Array Storage by Two-Dimensional Projections. As another example of a pure array code that also reduces the core storage requirements, we consider storage by two-dimensional projections, in particular, projections on two orthogonal walls and on the floor. Although a total of 500,000 bits of information are included in a 20 ft × 20 ft × 6 ft room with 2-in. resolution, storage of the three projections requires only approximately 4,000 bits of capacity. We temporarily assume that such a representation preserves without distortion the details of the environment and consider the question of the appropriate ray-tracing and data extraction algorithms.

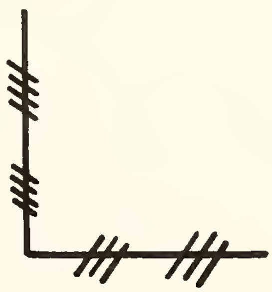
The three lists of coordinate pairs (x, y), (y, z), and (x, z) are formed from coordinate triplets calculated as usual by a 3D ray tracer. A two-dimensional data extraction algorithm checks the three arrays for the presence of a 1 in all three coordinate pair locations specified by a given triplet. If and only if the three locations are filled (contain a 1), is there a 1 in the spatial element corresponding to the triplet. We note that there may be a 1 in (x_0, y_0) and (x_0, z_0) but not in (y_0, z_0), meaning that there is no object material in (x_0, y_0, z_0). The algorithm proceeds through the triplets until it finds an intersection.

This algorithm is slower than the method with a three-dimensional array, because it requires three data extraction procedures, one for each projection, each slightly shorter than the one used with the 3D array. In addition, there is time consumed in the filtering out of "ghosts," or false information in the computer reconstruction of the environment.

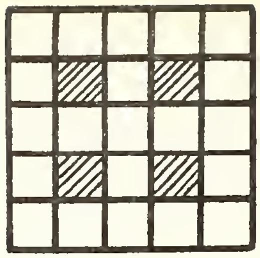
The existence of ghosts is easily seen in the following two-dimensional example, in which the shaded areas represent the existence of objects in the true floor plan.



If we choose to represent this information by the projections on two orthogonal boundaries, we obtain



Now consider the problem of reconstruction of the original area. There exists no unique solution, for there is not enough information in the projections to perform the reconstruction. Any procedure for reconstruction, such as one that fills in every square that has both its coordinates on the projections filled, makes mistakes. For example, this procedure results in the following version of the original floor plan shown above. The two new "objects" are the "ghosts."



With three 2D projections of the contents of a volume the same ghost problem arises. We recommend the following solution: the input of the environment to the computer is to be the correct three-dimensional data. The computer's master control program calculates, prior to an experiment, the three projections and the reconstruction from these projections obtained by filling in (x_f, y_f, z_f) whenever (x_f, y_f), (x_f, z_f), and (y_f, z_f) contain 1s in their planar arrays. By matching every filled entry, so constructed, with the filled entries in the original input data, the computer makes a list of the discrepancies. This list contains all the ghosts, locations filled in when they should not be.

Finally, after each intersection found by the data extraction algorithm, the computer looks up that coordinate triplet in its list of ghosts; if and only if the triplet does not appear, the intersection is a valid one. This procedure could be effected by a standard alphabetic search. Unfortunately, its use increases the discrepancy between the speeds using a 3D array code and that with a 2D projection array code. Thus this procedure too must be rejected because of speed.

Run-Length Coding. To begin the discussion of run-length coding, we distinguish three different types of such codes. Let us assume that we wish to store a representation of the occupied numbers from an ordered list, to be specific, 1, 2, 3, 8, 9, 13, 14, 15, 16. An array code, we recall, would store a block in which the 1st, 2nd, 3rd, 8th, 9th, 13th, 14th, 15th, and 16th bits would contain the value 1. If instead the numbers of the beginning and end of every block of 1s are stored in successive locations in memory, in our example, 1, 3, 8, 9, 13, 16, we denote this an "absolute list" run-length code. The second type is obtained by storing the initial number and the differences between pairs of succeeding numbers--for example, 1, 2, 5, 1, 4, 3. We call this a "relative list." Finally, there is a class of "hybrid" schemes, intermediate to the absolute and relative lists. The first hybrid scheme we denote the "mixed list"; it contains the values of the beginnings of blocks of one in absolute form and the end of the blocks in relative form, that is, relative to the beginning of each block. Thus, in our example, 1, 2, 8, 1, 13, 3 would be stored in successive locations in memory. The second hybrid scheme, actually a class of methods, uses an absolute value every K places throughout the list, and relative values

at all other places. For our purposes, K should be even; if K were four in the above example, we would store 1, 2, 5, 1, 13, 3. The mixed list is a hybrid scheme with $K = 2$. We note that every number should contain a marking bit to indicate if it is the beginning or endpoint of a block of ones.

The relative advantages and disadvantages of these schemes can be summarized in terms of a storage-speed trading relation. The absolute list takes the greatest number of bits to record all of the numbers in the list. Its data extraction algorithm, however, is simplest, because examination of any entry in the list yields immediately the location of a particular block of ones. The relative list, on the other hand, requires the fewest bits to code. The absolute value of any number is, in effect, coded as the sum of all previous relative values. The complexity of data extraction, however, increases greatly, for examination of an entry requires for full identification of its contents examination of all previous entries. We would require an algorithm to search for some register N in the list; this would require examination of the first P entries until the sum of these P entries either equaled or exceeded N. Whether N equals or is exceeded by the sum and whether P is even or odd then determines whether or not N is an occupied location. The hybrid procedures appear, as expected, intermediate in the trading location.

Three-Dimensional Run-Length Storage. Let us, however, consider an absolute list run-length code in terms of typical room characteristics. We estimate that a good room occupation density, the percentage of occupied elements, is from 5 percent to 20 percent, meaning that from 25,000 to 100,000 out of 500,000 are occupied. In a computer with 18-bit words, if one bit is used to identify whether a number is the beginning or end of a block of ones, a single word is limited to a maximum of $(2^{17} - 1)$, approximately 130,000. Thus two words are required for each number. What length of list can we expect? If we consider the type of linear ordering such as

$$\# = x + n_x(y - 1) + n_x n_y(z - 1),$$

the mean length of filled block would equal the mean length object along the x-direction (in feet) for a constant y and z, multiplied by the resolution (in grid lines/foot). Other similar ordering formulas obtained by permuting x, y, and z allow use of the y or z axes to maximize object continuity and consequently minimize the length of the list. We estimate a mean length of filled block to be between 10 and 20, and therefore a list length of between 2,500 and 20,000. A purely alphabetic search procedure in which the part of the list to be searched was successively subdivided into two parts would take up to 12 to 15 iterations. The search procedure may be somewhat improved by algorithms that invoke the correlations between element location and position of the surrounding locations in the list. Relative and hybrid procedures require more sophisticated decoding schemes and therefore yet longer calculation times.

It is apparent from the above discussion that run-length coding for the entire three-dimensional grid requires a lengthier data extraction program than does array coding; it must therefore be discarded. Besides, unless the density is unrealistically low, it provides only on the order of a factor of two savings in required capacity.

For completeness, we note that run-length multilevel coding and run-length two-dimensional projection coding are inferior to the corresponding array codes. Even with the array codes the problem is one of calculation time and not one of available core capacity. Thus it would be pointless to sacrifice more speed in an attempt to further reduce the storage requirements.

Vertical List Codes. The next approach is to consider mixed array and run-length coding, array coding for the two horizontal dimensions and run-length coding for the vertical dimension, or, alternately, run-length for the horizontal and array for the vertical. Yet the most significant characteristic of the schemes to be discussed is that a vertical list is stored only for those (x, y) pairs that contain at least one filled entry in the corresponding vertical column. The storage capacity required is thus approximately proportional to the density of ones in the floor projection.

A horizontal array code means the use of a square array containing a one at each (x, y) coordinate in which there exist any ones in the corresponding vertical strip of the 3D representation. Two-in. resolution in a 400-sq ft floor requires 14,400 bits, or 800 words of 18 bits per word storage capacity. Another 800 words are required to reference the sections in memory where the vertical information is stored. There will be a loss in speed associated with the referencing procedure, for the additional referencing word provides only the location of the block in which the corresponding vertical information is stored. The length of each such block may be from 0 to 18; the algorithm must identify the relative location in the block of the desired vertical information. In other words, if the algorithm finds a 1 in bit q of word w, it must count the 1s to the left of bit q in order to find the vertical list corresponding to bit q, word w in the block of vertical lists corresponding to word w.

If we assume a floor density of 5 to 10 percent, this requires 720 to 1,440 vertical lists. If these vertical lists are array coded, 6 ft at 2-in. resolution necessitates 36 bits or two words. Thus, if both horizontal and vertical information are array coded, 1,600 words + (1,440 to 2,880), or a maximum of 4,500 words of storage are required. Can we improve on this through use of vertical run-length coding? Since numbers from 1 to 36 require six bits for coding, and since in an absolute, relative, or hybrid list any of the numbers could be as large

as 35, we must save six bits for each number in a run-length list. Thus only if the vertical structure consists of a single block of 1s, may it be coded into a single word; otherwise, at least two words per vertical list are required. Thus this procedure effects no reduction in storage capacity and we therefore eliminate the possibility of horizontal array coding and vertical run-length coding.

Horizontal run-length coding and vertical array coding is less satisfactory yet. We have noted that array coding for the floor requires 800 words of storage. Again assuming 14,400 bits and an average length of filled block that is between 10 and 20, from 1,440 to 2,880 words are required for a run-length representation of the floor. Since the procedure is fundamentally slower, it has no advantages over an array coded floor projection and thus may be immediately discarded.

Clearly this horizontal projection vertical list scheme requires the least storage capacity and is fastest if both the horizontal and vertical information are array coded. In terms of the discussion just concluded, we summarize the properties of such a scheme. The horizontal array code requires 800 words, the referencing algorithm requires another 800 words, and, assuming a floor projection density of from 5 to 10 percent, the vertical lists require from 1,440 to 2,880 words, for a total of less than 4,500 words. This method of storage lengthens the data extraction procedure over a total three-dimensional array code only in that it requires an algorithm to count the number of ones to the left of a specific bit in a word, the method used to locate the appropriate vertical list.

Evaluation

The major result of the investigation is that all the procedures discussed are slower than a bullet ray-tracer, with stepping distance equal to one fifth the width of a grid element, coupled with brute force three-dimensional array storage. We have developed a multitude of schemes for reducing the magnetic core storage capacity requirements, the best among them, for small enough occupation densities, being the array floor projection, array vertical list code. The calculation time per iteration for the corresponding data extraction algorithm exceeds that for a pure three-dimensional array code only by the time required to count the number of 1s to the left of a particular bit in a particular word. We contend that in a small digital computer one could wire in a set of instructions (equal to the number of bits in a word) to carry out this function rapidly, using the appropriate word as the address of the operation. If this be done, the capacity problems are soluble, and the major remaining problems to evaluate are calculation accuracy and speed.

The only inaccurate procedure introduced has been the bullet ray-tracer, in which any desired degree of accuracy,

any probability, per iteration, of missing a corner, may be obtained through the use of a small enough stepping distance for the bullet. In Appendix 1 we make and justify assumptions about the probability density functions of dummy sensor position within a square and exploring ray angle to derive the two-dimensional relation between the probability of missing a corner and the ratio of stepping distance s to square width d. The result states that the probability of missing a corner is proportional to s^2/d^2, in particular, a choice of d/s of five gives a miss probability of approximately 0.01.

If we assume a square room $120d \times 120d$, and a stepping distance of $0.2d$, then the maximum number of steps required is approximately 850. The data extraction algorithm will certainly require no more than 240 iterations if a filtering algorithm is inserted between it and the ray tracer so that the same element is checked once only. (The need for this arises because some of the coordinates, rounded off to integer multiples of d, will appear several times in the "list" of outputs from the ray tracer.) To discuss the final issue of speed, we recognize that the data extractor takes longer than the ray tracer and filtering algorithm, and so for simplicity we assume 400 iterations of a combined ray tracing and data extraction algorithm.

Because the probability per iteration of missing a corner, averaged over all orientations of exploring ray, is 0.01, and because corners are missed most frequently when the ray points diagonally across the room, the maximum length ray should miss, on the average, more than eight or nine corners. Thus for a truly satisfactory simulation we must use a shorter stepping distance s, thereby reducing the error probability per iteration in proportion to s^2, but simultaneously increasing the number of iterations as $1/s$. The expected number of missed corners should therefore be proportional to s. Alternately, we can introduce a checking algorithm, based on the principles of ray tracer 4, which locates missed corners. Finally, the best alternative may be to abandon the bullet procedure in favor of the slightly slower but accurate ray tracer number 3.

In the following section we shall see that a single iteration of a 2D bullet ray-tracer coupled with a 2D array data extractor requires approximately 0.5 msec on the TX-0 computer. 400 iterations therefore means 200 msec, 200 times our stated goal of a millisecond. Extension of the simulation to three dimensions will increase the computation time by 25 to 50 percent. Prominent among the weaknesses of the TX-0 in carrying out the algorithm is the 12 microsecond average instruction time. Nevertheless, considering the state of the art in digital computers, it is not reasonable to expect shortly a small computer that will perform the calculations more than five times faster, or a large computer to perform it more than ten times faster. Besides, we cannot expect non-time-shared use of a large computer such as the 7094. Thus we are two orders of magnitude short of our goal in speed. We therefore must reject

simulation with a standard digital computer if we are to preserve our standards of generality and naturalness in the room environment and accuracy in the simulation calculations.

If either it proves impossible to develop into operation the special-purpose storage and scanning devices proposed later in this paper, or if new digital computers carry out with greater speed the techniques thus far discussed, then these procedures may prove to be of direct use. The technological developments could be of four interrelated kinds--decrease in machine cost, decrease of machine cycle time, increase of available core storage, and development of rapid machine language instructions that carry out functions appearing in our algorithms, operations more complicated than the basic data transfer, arithmetic, and test instructions. In the eventuality that such developments bring standard digital computer simulation into the ballpark of a millisecond per calculation, then the present considerations will provide insight and a variety of algorithms with which to tackle the storage-speed-accuracy-generality of environment trade-offs for a particular digital computer.

We have seen, for example, that in a pure array code, if $N = n_x n_y n_z$ is the number of volume elements, the storage capacity C is proportional to N. In the array floor projection, array vertical list code, if δ_f is the floor projection occupation density, then C is proportional to

$$2n_x n_y + \delta_f n_x n_y n_z = n_x n_y (2 + \delta_f n_z)$$

Thus $(2 + \delta_f n_z)/n_z$ is a measure of the percentage saving in storage capacity through the use of the latter method.

In general, the computation time T is proportional to the number of intersected elements, and therefore grows roughly in proportion to $\sqrt[3]{N}$. For the simplest ray tracer, the bullet procedure, however, T is approximately proportional to $(\sqrt[3]{V})/s$, where V is the volume and s is the bullet stepping distance. The volume V is equal to Nd^3, where d is the width of a cubical unit element. Thus if $(s/d)^2$ is held constant to yield a particular probability per iteration of missing a corner, then again T is proportional to $\sqrt[3]{N}$. Restriction of the simulator to a certain range of efficacy permits reductions in calculation time. For example, if a value of the bullet stepping distance s is chosen, then the maximum computation time is proportional to the maximum number of steps, or the range of sensor exploration.

A satisfying feature of the simplest brute force techniques is that environment generality has no effect on maximum calculation time. Compromises in generality would, however, be advantageous for two-level coding and for storage by two-dimensional projections. Such relations furnish the key to successful exploitation of the trade-off potentialities, should some breakthrough make feasible this class of techniques.

Postscript: "Environment-Specific" Algorithms

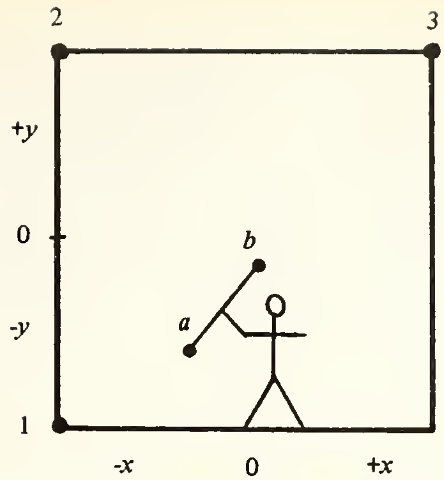
We have considered general techniques that would apply to all room environments and enable highly accurate calculations at rates, unfortunately, two orders of magnitude short of the goal. There remains another less satisfactory technique which should be explored further if it should be necessary to simulate with standard digital computer only. This technique is the use of individual simulation programs, based on the principles developed in these sections, that are ideally suited to each particular room environment. Object-centered, brute force, or combination methods could be used. In each situation the algorithm and the room environment would be jointly tailored to afford the best compromise among speed, naturalness of the environment, and calculation accuracy. It is clear that with enough compromises in the latter two categories we can attain our goal in speed, for instance, by reducing the number of surfaces to one planar section, a trivial situation that is, unfortunately, totally useless. On the basis of our investigation, we contend that even with individual adjustment of the program to the environment it will prove impossible to attain a truly satisfactory compromise among speed, environment generality, and calculation accuracy.

4. TWO-DIMENSIONAL "BRUTE FORCE" SIMULATION ON THE TX-0 COMPUTER OF A RANGE-ONLY, PENCIL-BEAM SENSOR

To stimulate insights about the eventual functioning of a mobility aid simulator, and perhaps to run preliminary experiments, we are considering setting up a small-scale, two-dimensional simulator on the TX-0 computer. In this section we outline this project briefly with an emphasis on the systems and programming aspects; a complete hardware description is to be found in the forthcoming doctoral dissertation of Emanuel Landsman, who has designed all the electronics to which we allude in this section (6).

Monitoring the Dummy Sensor Position and Orientation

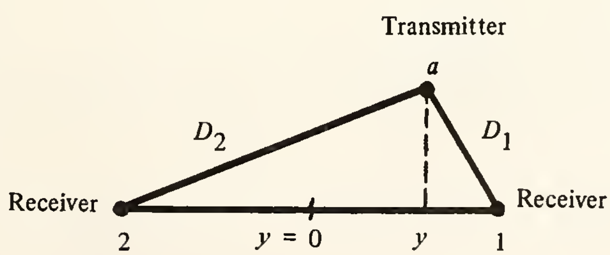
Mounted on the dummy sensor, separated by a distance of approximately 1.5 ft, are two 40 kc ultrasonic transmitters. Each emits, every 60 msec, a burst of approximately 1-msec duration. For the two-dimensional simulation, there are three ultrasonic receivers, located at an identical height in positions as shown in the following floor plan:



Let us analyze the operation of receivers 1 and 2, which measure the *x*-coordinates of points *a* and *b*, upon the signals from transmitter *a*. The transmission of the signal from *a* initiates a ramp waveform; the reception, at time T_1, by receiver 1 triggers an integration of the ramp; and, finally, the reception, at time $T > T_1$, by the second pickup marks the value on the parabola. This value is proportional to $(D_2^2 - D_1^2)$. An application of the law of cosines shows that y also is proportional to $(D_2^2 - D_1^2)$. Similarly, pick-ups 2 and 3 measure the *x*-coordinates. The true distances from transmitter to receivers are actually dependent upon their relative vertical displacement but because this is identical for all pickups it cancels when the difference $(D_i^2 - D_j^2)$ is formed.

Transmission of the Monitor Output to the TX-0

Thus the monitoring system provides four analog voltages that are proportional to the signed x and y coordinates of dummy sensor positions *a* and *b*. Two of these values are updated every



30 msec, suggesting that we update every 60 msec the complete set of monitor inputs to the computer. The four signals are continuously present on four transmission lines running from the testing room to the TX-0. The computer performs less than 60 msec of calculations on the previous set of data, and then enters a "listen-loop" in which it waits for a ground level at the TX-0 external flip-flop input. The change from -3 V to ground is triggered by a "ready with new data" pulse sent every 60 msec from the experimental room. The ground level transfers the computer into its input routine, and sets an external switching gate to position 1.

In position 1, the gate connects one data line to the input of the Datrac, the TX-0 analog-digital converter. An "ex0" instruction strobes the number through the Datrac; an "ex1" instruction strobes the value into the live register and steps the electronic switch to its next position. From the live register the data is transferred into a core storage block. Either the "ex0" instruction or the "ex1" instruction may be used to reset the external flip-flop level back to -3 V. This process is thrice repeated, with the result that all four values are stored in memory. The program then begins to calculate with this data. Finally, an "ex2" instruction is used to transmit the calculation output through a digital-analog converter and over a transmission line to the testing room, there to control a display for the subject. Its cycle complete, the computer re-enters the "listen loop" to wait for more data.

Representation of Numbers and Calculation Accuracy

The present experimental room is 12 ft × 12 ft. Because the simulation is two-dimensional, all obstacles effectively extend from floor to ceiling. We use the bullet ray-tracing algorithm and brute force storage with a 32 × 32 matrix of squares, each of width 4.5 in. Our calculations, however, must be done with numbers having more significant figures, to reduce errors that multiply with algorithm iterations. If we represent all coordinates to units of, for example, 1/16 d, each original number is accurate to within ±1/32 d, and differences are accurate to within ±1/16 d. Multiplying this round-off error by the number of iterations gives an upper bound to the error along each dimension at the far end of the exploring ray.

The maximum final error is thus so sizable after 50 iterations that we should examine more closely the nature of the error. An accuracy of ±1/32 d, with d = 4.5 in., corresponds well to the expected random error of ±1/8 in., so it would be pointless to adopt finer calculation resolution with the present state of the monitoring equipment. The two transmitters are separated by approximately 1.5 ft. Thus, if the bullet stepping length were chosen to be 1.5 ft, there could be no greater error along one dimension than

$$\left(\frac{12\ ft}{1\ 1/2\ ft/\ 2}\right) \times (\pm)1/16\ d,$$

or approximately $\pm 3/4d$. However, because the probability of missing a corner with the bullet procedure varies as (s^2/d^2), the square of the ratio of stepping distance to square width, we shall not be satisfied with a stepping distance of 1.5 ft. Therefore we attempt to reduce the stepping distance, thereby increasing the percentage error in the x and y stepping increments. The propagating error increases in direct proportion to the number of iterations, and to (d/s). The difficulty is seen vividly by noting that a step size of 1/8 d and a coordinate representation in units of 1/16 d allows at most 5 $(\Delta x, \Delta y)$ pairs for positive Δx and Δy

$$(1/8\ d,\ 0),\ (1/8\ d,\ 1/16\ d),\ 1/16\ d,\ 1/16\ d),$$
$$(1/16\ d,\ 1/8\ d),\ (0,\ 1/8\ d).$$

This depends, of course, on the computer's round-off procedure; an alternate method of truncation would permit three pairs only. In short, the angular resolution is terrible.

The best solution is adoption of a representation with yet more significant figures. Five more bits would allow a step size of d 8 with a total propagated round-off error, less than $\pm 3/4$ d, equal to that in the above case, in which the step size is 1.5 ft = 4 d. Further improvement through use of more bits in the representation would be meaningful only with a higher monitoring accuracy. If all bits in the word were already utilized, another approach is precalculation with a large stepping distance several of the points along the path, the k^{th}, $2k^{th}$, $3k^{th}$, . . . points corresponding to the eventual small stepping distance. The k^{th} coordinate replaces the k^{th} value in the fine stepping calculation; the $(k + 1)^{st}$ point is calculated from the k^{th} as reference. Repeating this procedure at points $2k$, $3k$, . . . prevents the propagation of errors beyond $(k - 1)$ iterations.

The initial version of the program tolerates the inaccuracy and calculates to a resolution of $(d/2^4)$, with coordinate values, therefore, from $-(2^8 - 1)$ to $+(2^8 - 1)$; grid coordinates are computed by shifting the numbers to the right four places. We take 8 bits plus a sign bit as an output from the monitoring equipment, and calibrate the system by precalculating a proportionality constant for each dimension. The constant is chosen so that, when multiplied by the greatest positive (negative) output signal from the monitor, it gives as a product $+(-)(2^8 - 1)$. The proportionality constants are stored to nine-bit accuracy, with separate registers containing the decimal point locations.

The Program

Thus the "listen loop" is followed by an input routine and a data conversion routine to appropriately normalize the four coordinates. The starting point of the scan, (x_0, y_0), is set

equal to (x_b, y_b); the bullet increment, (d_x, d_y), is set equal to $(x_b - x_a, y_b - y_a)$, divided by 2^5. Following each step of the bullet procedure, the data extraction algorithm locates the corresponding bit by the procedure of the preceding section, in which the identification number is calculated by $\# = x + (2^5)y$, for positive x and y. If $x[y]$ is negative, it is replaced by $(x - 1)[(y - 1)]$.

The TX-0's lack of a multiply instruction is detrimental in the input conversion routine, where consequently we must multiply by subroutine, but not in the data extraction algorithm. where we multiply by table look-up. Even for a $120d \times 120d \times 36d$ room, the multiplication table for an array code would at most be of length 240, and thus may easily be stored. The TX-0's lack of multiple shift or cycle instructions with controllable length of shift wastes time, especially in the data extraction algorithm,

An estimate of the time consumed by the data input and conversion routines is 7 msec. Most is consumed by the multiply subroutine, which would be unnecessary for a machine with a multiply instruction. Since one iteration of the bullet ray-tracer plus data extraction takes roughly 500 to 600 μsec, the present system is limited to a maximum of 60-7 = 53 msec divided by 600 μsec or approximately 90 iterations. Since 90 iterations of an 1/8 d stepping distance may fail to intersect a wall, we provide an output signal of "333" to indicate this case. Otherwise the output is the number of bullet steps prior to intersection. A 90-iteration limit corresponds to a mobility aid with a finite range of efficacy, in this case, approximately $11d$, almost 4 ft.

SIMULATION WITH STANDARD DIGITAL COMPUTER PLUS SPECIAL PURPOSE SCANNER AND RANGE FINDER

Philosophy of the Approach

We find that simulation by available standard digital computers falls two orders of magnitude short of the goal of 1,000-range-only, pencil-beam calculations per second. The following argument illuminates the difficulty of the task: The calculations described involve on the order of 100 to 1,000 serial processes, such as iterations, interpolations, and searches. (Serial execution is imposed more fundamentally by the serial nature of today's digital computers than by an intrinsic quality of the calculations.) Thus each "subcalculation" of the types discussed earlier must be completed in one to ten microseconds, an impossible task unless average machine instruction times are reduced to the order of 0.1 μsec.

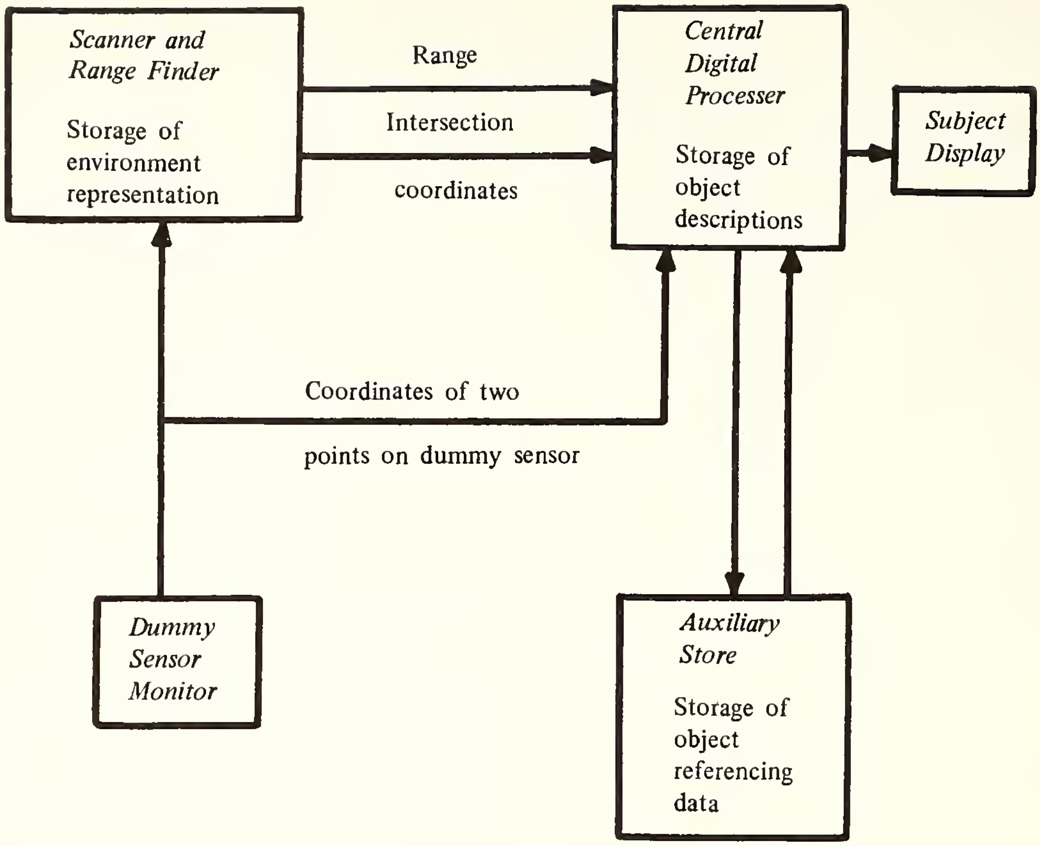
Why is a digital computer ill-suited to these tasks? The bottlenecks arise at two points, the ray-tracing algorithm, and the data extraction algorithm. The ray-tracer consumes time because the computer must iterate a process such as coordinate

indexing or labeling and interpolating between intersections of a ray with a grid of parallel lines. The ray-tracer cannot be "turned on" and left to function by itself; the instruction must be given again and again, several hundred times. We seek, therefore, to replace the digital computer ray-tracer with a device that performs an initial calculation to trigger a self-sustaining scan along the appropriate path.

One can think of the data extraction bottleneck as the severe distortion of space undergone between the real room environment and its representation in the computer. The object-centered approaches store parameters of the equations of the lines and surfaces that describe the exterior of the room objects. The brute force approaches store a list of the contents of elemental volumes. With a reasonable ordering of elements, the mapping distorts severely along two dimensions and preserves some continuity along one dimension, yet only in blocks of length equal to the number of bits per computer word. If one thinks of the computer representation as a code for the data, the complexity of the corresponding decoding algorithm is the cause of the lack of speed. There is an additional delay due to the look-up function; once the proper location is referenced, the interrogation is not automatic but requires an additional set of instructions. Consequently, we seek a device that preserves the interior room structure as closely as possible in its representation of the environment, thereby facilitating the decoding or data extraction task. The search and interrogation functions of this device should be integrated, overlapping as closely as possible.

In summary, then, we seek a scanner initially set and triggered by calculated parameters but thereafter self-sustaining, with the character of the scan simplified by an appropriate choice of environment representation. We suspect that a good choice will minimize the distortion introduced by the mapping from true room structure to stored representation. Finally, the search and interrogation functions should be integrated. We exclude from consideration, however, the most perfect "solution" satisfying these criteria, the construction of a small-scale version of the room in which a small-scale sensor moves in position and orientation equivalent to the subject's dummy sensor. If this method requires construction of a small-scale prototype of every mobility aid to be tested, it negates the philosophy of general-purpose simulation.

We therefore propose a simulation system described by the following block diagram. The central digital processer and auxiliary storage unit are instrumented by what we have called a standard digital computer; however, contrary to the approach of past sections, the scanner and range finder is a separate, special-purpose unit, functioning independently of the digital processer. In fact, we shall show that the scan parameters may be obtained by auxiliary circuitry and without the central digital processer. In the next section we elaborate further on the functions of the central processer and of the auxiliary storage unit.



The most promising potential implementation of the scanner and range finder appears to be a flying spot scanner coupled with brute force, photographic film storage. A special-purpose waveform generator and control circuit calculates the parameters of the electromagnetic or electrostatic control signals and propels the cathode ray tube scanning beam over the path to be searched. Meanwhile, the digital processer is free for other calculations. The fluorescing light from the screen sweeps out the path across a photographic film on which the room environment is brute force stored by a matrix of transparent and opaque elements. When light passes through a transparent element, an intersection is recorded; a special circuit notes the position and calculates the range.

With this system we have a rapid analog scan instead of a laborious digital calculation of points to be scanned. The search and interrogation functions are almost simultaneous. We shall discuss two mappings of the three-dimensional environment onto a plane by slicing three-space into horizontal sections and placing them side by side, and shall describe the performance and hardware implications of these two procedures.

Finally, we shall discuss a new cathode ray positioning technique and an idea for a three-dimensional array of storage elements with special-purpose access circuitry. We wish to encourage further searches for special-purpose hardware well suited to the mobility aid simulation task.

Single Channel Flying-Spot Store and Scanner

A diagram of the single channel flying spot store and scanner is given in Figure 1. The optics are adjusted so that deflection of the beam to a particular point on the screen focuses the light upon the corresponding point in the film storage plane, where a transparent (opaque) spot transmits (blocks) the light and thereby registers the presence (absence) of object material. We shall explore the nature of the brute force storage plane representation of the room environment, the resulting shape of the scanning pattern, and an approach to generate the requisite scan control signals. Assuming a total capacity on the order of 1,000,000 bits, we consider questions of speed and resolution, describe functionally the auxiliary circuitry required by the range finder, and list the major technical problems that will be encountered in development.

The Scanning Pattern. We propose to slice horizontally the three-dimensional grid and spread the planar matrices of 0s and 1s into the pattern of Figure 2 in which, for simplicity, there are sixteen z levels. A typical scanning pattern is shown in the diagram of Figure 3. Here the exploring ray travels from point $b(z = 2)$ to point $c(z = 9)$. In both electrostatic and electromagnetic cathode ray tubes x and y deflections are separately controlled, and are approximately proportional to the electrostatic plate voltage and the magnetic coil current, respectively. To determine the nature of the required waveform generators, we must therefore find the general form of the x and y deflections and the parameters that determine each individual waveform.

The x and y deflection waveforms corresponding to the above example are shown in Figure 4. We further decompose each waveform into a sum of a step and a ramp, as shown in Figure 5. In general, how many parameters are needed to characterize these waveforms? Each ramp requires two numbers, the value at $t = 0$ (x_{r0}, y_{r0}) and the slope (m_x, m_y). Each step requires four parameters, the value at $t = 0$ (x_{s0}, y_{s0}), the initial time duration (T_{x0}, T_{y0}), the size of step $(\Delta x, \Delta y)$, which takes on the values of $+L$ and $-L$, and the standard periodic time duration (T_x, T_y). (The initial time durations will differ from the standard time durations unless the scan is begun at the interface of two z-layers.) Finally, the parameter T_{tot} is the duration of the entire scan.

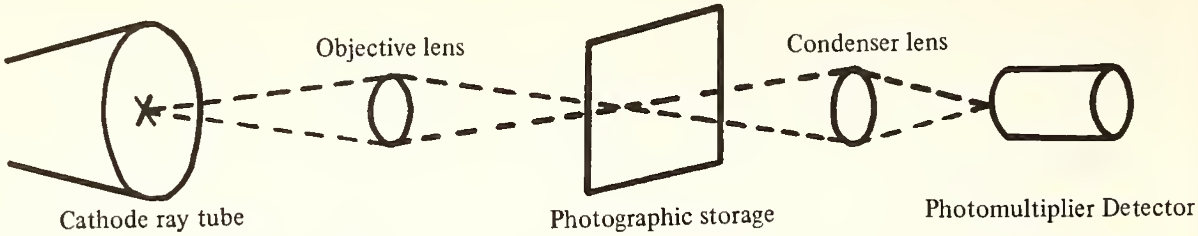


Figure 1. Single Channel Flying Spot Store and Scanner

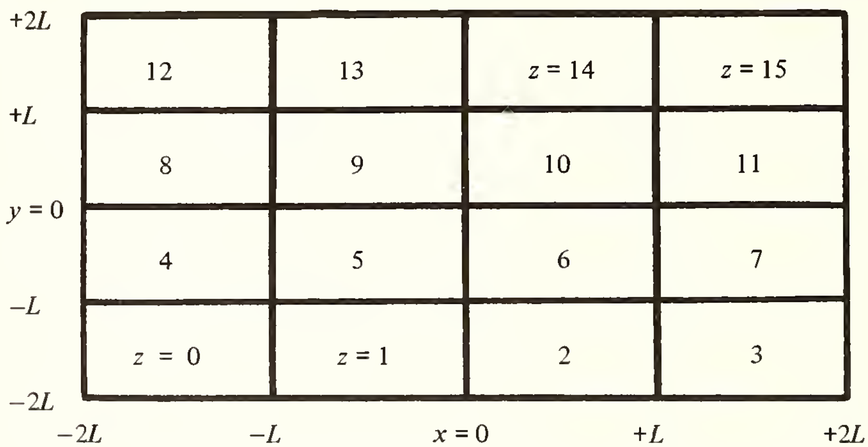


Figure 2. Arrangement of Z Levels in Photographic Storage

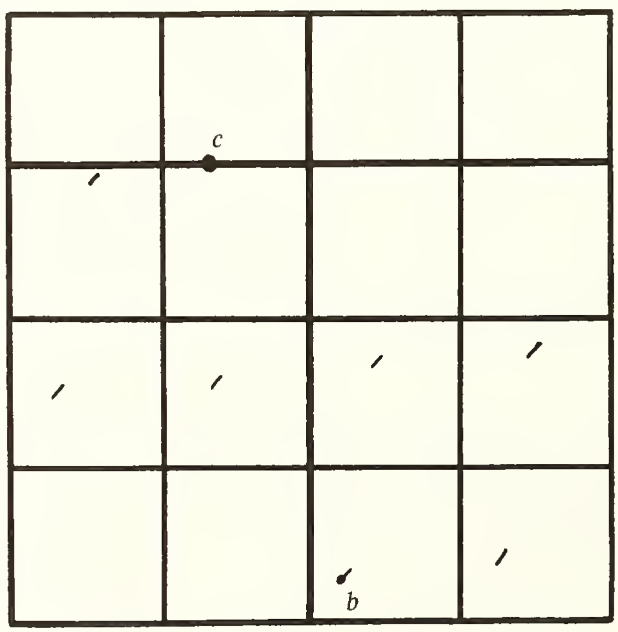


Figure 3. A Typical Scanning Pattern

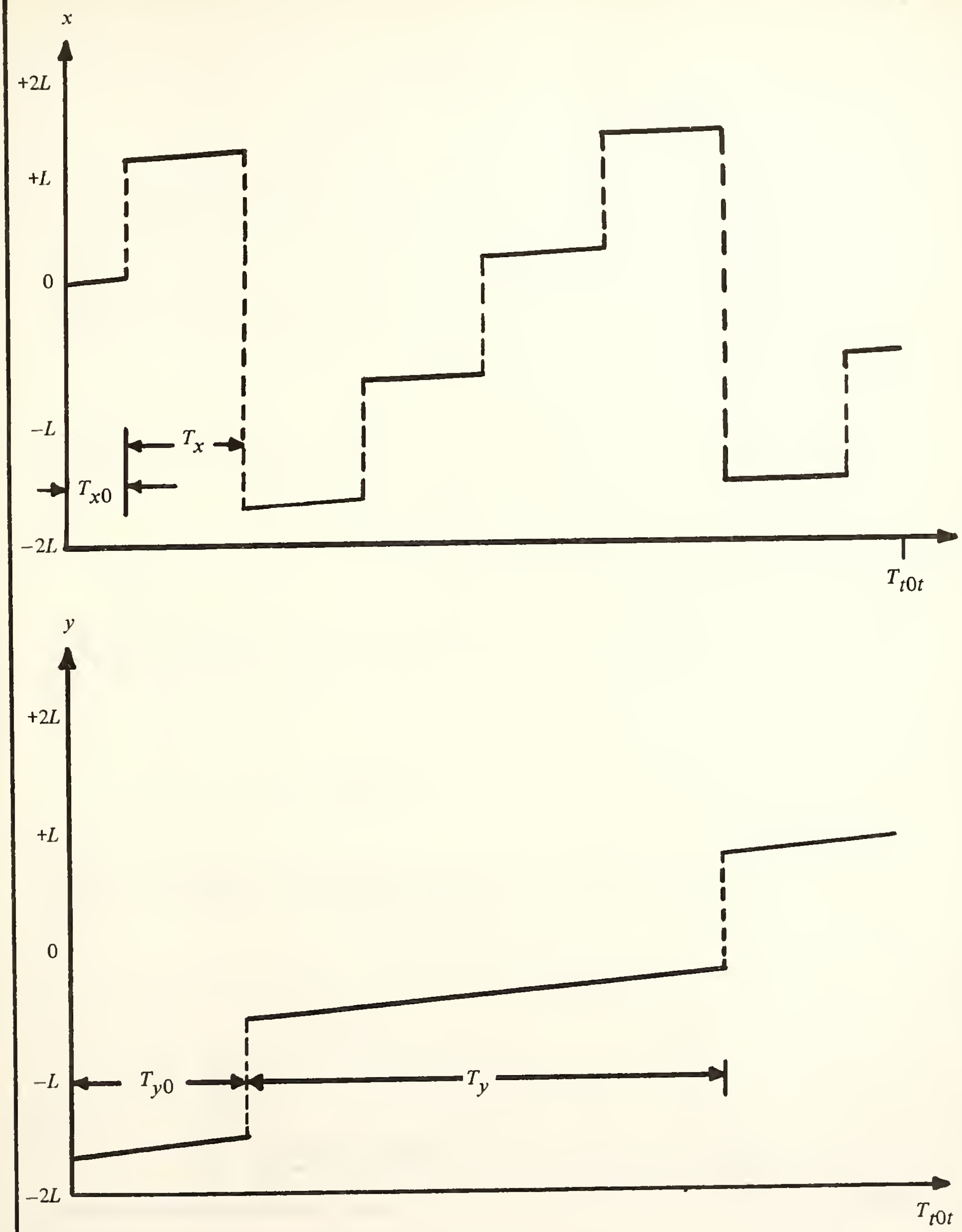


Figure 4. X and Y Deflection Waveforms of Scanning Pattern in Figure 3

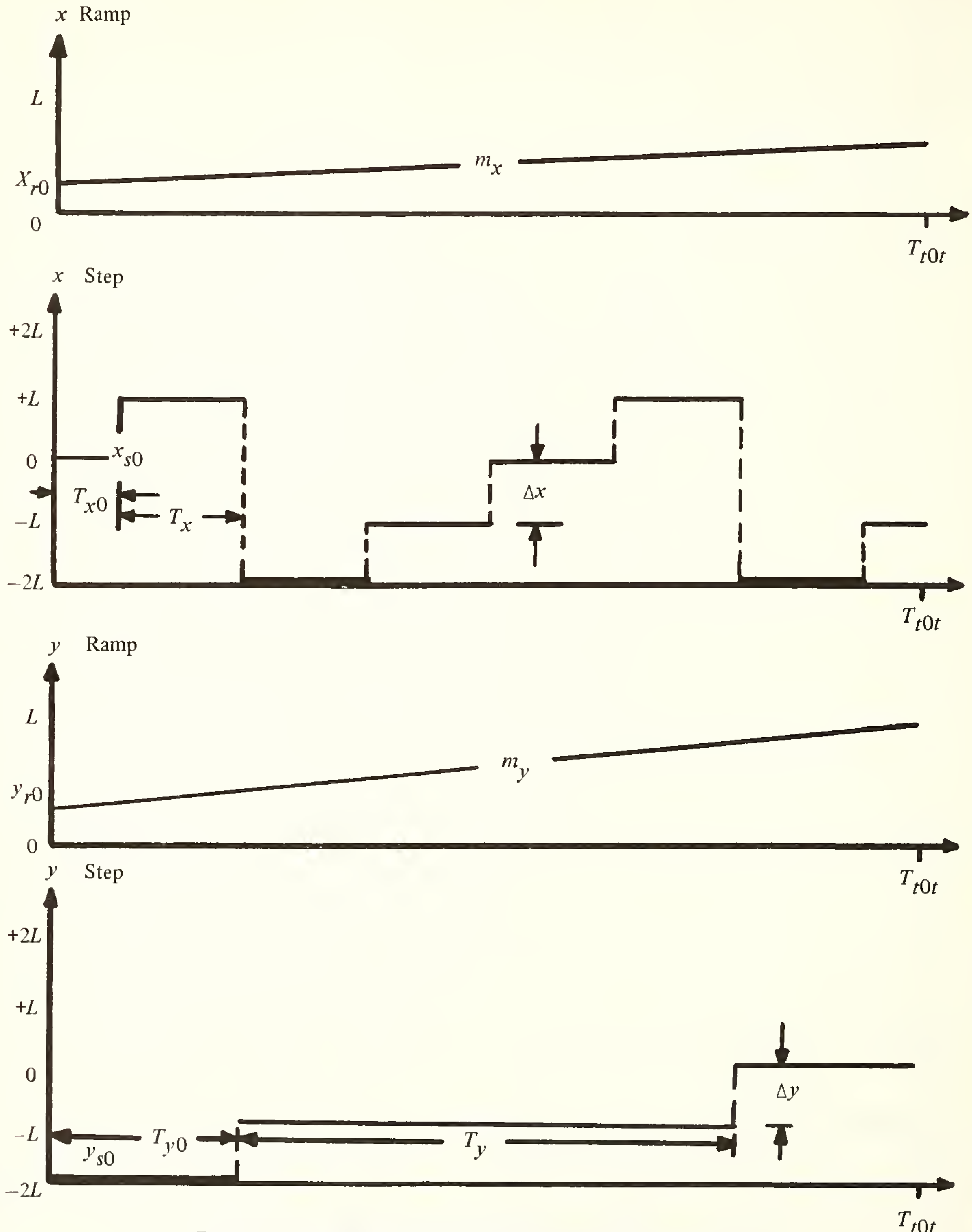


Figure 5. Decomposition of Deflection Waveforms in Figure 4 (Waveform = Ramp + Step)

How many of these thirteen parameters are independent? How may all be determined from (x_a, y_a, z_a) and (x_b, y_b, z_b) coordinates of the dummy sensor? We assume that all numbers are expressed in units of d, the length of the cubical unit element, and that, to be specific, $z = 0$ to $z = 16$ is divided into 16 horizontal slices, arranged in the pattern shown in Figure 2. It should be clear that if the floor plan is divided into an $n \times n$ matrix of squares, then the side L of the large square representing one z layer is equal to n. The coordinates of the exploring ray's starting point are (x_b, y_b, z_b); (x_a, y_a, z_a) determine the ray's direction.

Formation of Scanning Parameters. The ramp starting points, x_{r0} and y_{r0}, equal x_b and y_b, respectively. The equations

$$\frac{x_b - x_a}{z_b - z_a} = \frac{m_x T_x}{1} \quad \text{and} \quad \frac{y_b - y_z}{z_b - z_a} = \frac{m_y T_x}{1}$$

relate the x and y motion to the z motion, and we may therefore choose

$$m_x = k(x_b - x_a)/(z_b - z_a)$$

and

$$m_y = k(y_b - y_a)/(z_b - z_a).$$

x_{s0} is equal to $\{[(\text{integer part of } z_b/\text{mod } 4)]L - 2L\}$, where the truncation operation identifies the z-layer, and the modulo and subtraction operation are determined by the nature of the sixteen square pattern. Similarly, y_{s0} is equal to $[(\text{integer part of } z_b/4)L - 2L]$. If z increases (decreases) along the ray, then

$$\Delta x = +(-)L = \Delta y.$$

Although the x-step waveform jumps in cyclic fashion modulo $2L$ through the levels $(-2L, -L, 0, +L)$, the y-waveform assumes each value once only.

If z increases (decreases), T_{x0} is proportional to the difference between z_b and the integer equal to or just greater (less) than z_b. T_{y0} is calculated identically except for the use of the multiple of four nearest to z_b. By analogous reasoning, T_x is proportional to 1 and $T_y = 4T_x$. Although T_{tot} could also be expressed in terms of screen distances and slopes, it seems best not to calculate T_{tot} but rather to allow tne end of the scan to be detected by "overflows" in x, y, or z. The $x(y)$ overflow occurs when an increasing $x(y)$ ramp reaches L, or when a decreasing value reaches 0. The z overflow occurs, if z is increasing (decreasing) when y_{step} tries to jump from $+L(-2L)$.

Next we attempt to devise a digital computer calculation scheme that minimizes the delay between the input of (x_a, y_a, z_a) and (x_b, y_b, z_b) and the output of the above twelve parameters. The first step is input of the six coordinates and multiplication by suitable precalculated factors to convert them into units of d. In order to save digital calculation time, this could be accomplished externally by amplifiers or potentiometers preceding the analog-to-digital conversion and subsequent input to the computer. x_{r0} and y_{r0} are set equal to x_b and y_b, respectively. x_{s0} and y_{s0} are formed by a combination of masking, shifting, addition, and table look-up, or more quickly through table look-up referenced by the integer part of z. Δx and Δy are obtained by testing the sign of $(z_b - z_a)$.

It is important to note that only the calculated relative values, and not the absolute values, of m_x, m_y, T_{x0}, T_y, T_x, and T_y are significant, for the waveforms can be compressed or expanded and the slope of the ramps changed at will by auxiliary circuitry. Such shifting of the time scale will be incorporated, for example, by changing the period of timing pulses triggered by a relaxation oscillator. So we assume, without loss of generality, that the output digital control signals be only proportional to the required slopes and time intervals. Thus, for simplicity, we let

$$m_y = (y_b - y_a)/(z_b - z_a)$$

and

$$m_x = (x_b - x_a)/(z_b - z_a).$$

T_x is set equal to 1 and T_y to 4. If z increases (decreases), T_{x0} is set equal to the difference between z_b and the adjacent higher (lower) integer. Finally, T_{y0} is obtained from T_{x0}, if z is increasing (decreasing), by adding to it

$$(1 - x_{s0}/L)\ [(2 + x_{s0}/L)].$$

(x_{s0}/L) can be found either by shifting x_{s0} to the right $\log_2 L$ places or by a table look-up referenced by the integer part of z.

Calculation of the Scanning Parameters Without Use of the Digital Processor. As the final step we consider whether the identical calculations could be easily instrumented by auxiliary circuitry without use of the digital processor. We assume the existence of appropriately calibrated amplifiers to perform the requisite normalization of the analog coordinate signals, and henceforth take the values as normalized. Clearly,

$$x_{r0} = x_b,\ y_{r0} = y_b,\ T_x = 1,\ T_y = 4,$$

and

$$\Delta x = \Delta y = (L)\ (z_b - z_a)/[z_b - z_a]$$

may be formed by trivial analog circuitry. Calculation of m_x

and m_y is accomplished by an analog divider. Passing z through an analog-digital converter and taking only the high order bits is used to obtain the integer part of z; if there are only sixteen values, a reasonably sized diode network may perform the table look-up function and obtain x_{s0}, y_{x0}, and (x_{s0}/L). Another similar, slightly more complex, truncation and gating procedure, controlled by the sign of $(z_b - z_a)$, will yield T_{x0}. Finally, the difference between T_{y0} and T_{x0} is obtained by a gating network controlled by (x_{s0}/L) and the sign of $(z_b - z_a)$.

The only class of special case that requires comment is that of small $(z_b - z_a)$, which occurs whenever the dummy sensor is held close to horizontal. If $(z_b - z_a)$ equals zero, this can be identified immediately and used to activate a simpler scanning control in which there are no jumps. $T_{x0} = T_{tot}$ is not calculated, and the scan is halted either by intersection or by x or y overflow. $T_{x0} < 1$, and a small $(z_b - z_a)$ resulting in a proportionately large (x, y) deflection, too large to be traversed within that time, is a potential source of trouble. This case too could be detected and handled by appropriate special-purpose logic, dependent upon the scanning characteristics of a particular cathode ray tube.

The conclusion is that the twelve waveform control parameters may be formed, without calculations by the digital processor, using procedures that apparently require relatively simple auxiliary instrumentation. We choose not to consider the hardware aspects of the circuitry, but we instead tackle the problem of production of the control waveforms, given the twelve control parameters, properly normalized, in analog or digital form. We assume the existence of a network that detects x, y, and z overflows and therefore halts the scan at the appropriate time. (If the environment is such that there is always an intersection, then this network is not needed.)

Production of the Control Waveforms from the Control Parameters. We first consider the production of a ramp of controllable starting point and slope. The starting point is a voltage or current signal equal in value to the analog output of x_{r0} or y_{r0}. If a step function is integrated to form the ramp, the height of the step is proportional to the slope of the ramp. Thus integration from $t = 0$ of a constant signal proportional to m_x or m_y and addition of the resulting ramp to a constant equal to the starting point value gives for positive t the desired ramp waveform.

Next we discuss the formation of a step waveform with controllable starting point, step value, initial time duration, and periodic time duration. The starting point is set by the output of x_{s0} and y_{s0}. The appropriate size and direction of step, always a multiple of L, is gated by a switching network controlled by Δx, Δy, and the current value of the step waveform, and triggered by signals at the end of each time increment. The initial

durations may be formed by adjusting an initial voltage or current in a monostable circuit. Finally, a clock triggered by the end of intervals T_{x0} and T_{y0} provides the periodic time intervals $T_x = 1$ and $T_y = 4$.

The above considerations suggest one possible approach to the design of the required control circuitry. The point is that the design appears feasible with standard analog and digital componentry and techniques of waveform generation. We postpone for future research hardware design and problems of sensitivity, stability, and timing.

Scanning Speed, Storage Capacity, and Deflection Precision. Two other major issues are scanning speed and storage capacity. Typical edge-to-edge cathode ray tube deflection times, which generally are deflection power limited, range from 20 to 40 μsec. Typical point-to-point deflection times range from 1 to 2 μsec, and are limited by the bandwidth of the control circuitry and by resonance phenomena in the electromagnetic yoke. We assume j^2 z-levels, arranged in a square array, as above with $j = 4$. In the worst possible case, the scanning beam falls in all j^2 sections, makes $(j^2 - 1)$ jumps, and traverses the screen roughly j times horizontally and once vertically. We therefore take as a rough upper bound for scanning time $(j + 1)$ times the 40-μsec peak-to-peak deflection time plus (j^2) times the 2-μsec point-to-point deflection time. If $j = 6$, the scanning time should not exceed 350 μsec, 1/3 of a msec, and is therefore satisfactory.

Let us assume that we require 1,000,000 bits of brute force storage capacity, or a scanning resolution of 1,000 × 1,000 points. Television cathode ray tubes scan 500 lines, but the precision required is not one of absolute positioning but only of relative positioning. Even then some drift is acceptable for television. The Bell System, seeking an accuracy of ±0.1 spot in a 500 × 500 array, noted that this required control signals accurate to ±0.02 percent and therefore designed its scanner with a closed loop feedback circuit to position the beam (4, 5). The MIT Cognitive Information Processing Group, in which this project was undertaken, is presently operating a flying spot scanner with 300 × 300 resolution, but is beginning development of 1,000 × 1,000 resolution with a reliability of (±) one part in 1,000. Thus our goal, while technologically feasible, represents a difficult task of highly precise instrumentation. One method of relaxing these severe demands on precision is presented in the section below entitled "Optically Multiplexed Flying Spot Store and Scanner."

Data Read-in and Read-out; Measurement of Intersection Position and Range. The flying spot scanner may be used to prepare storage plates for each room environment. The digital computer directs the beam to those positions where darkened spots should exist in the planar representation of the data. Thus spots on a previously unexposed film are darkened, one at a time, until an entire planar array is written.

Required for the reading operation is a gate that prevents reading during the beam jumps. In principle, this may be accomplished either by turning off the electron beam while discontinuously repositioning it or by gating off (not looking at) the photomultiplier output during these brief intervals. The photomultiplier current output is proportional to input power; if one used instead a detector that measured energy, and if the spot traversal time were significantly different when jumping over or scanning a spot, then the problem would be solved by the choice of an appropriate threshold to trigger the detector.

A positive output from the photomultiplier, signifying an intersection, must immediately trigger the cessation of the scan. It could also cause the halt of a high frequency counter that begins at the start of every scan; however, this output cannot in general be used to measure range, for it is a multivalued function of range that depends intrinsically on the relative scanning speed and repositioning speed of the beam. How, then, are the range to and the position of an intersection to be measured? The values of the x and y ramps at the cessation of the scan are the final x and y values of the intersection. The integer portion of z may be obtained from a gating network with inputs of the final values of the x and y stepping waveforms and outputs of $z = 0$ to $z = (j^2 - 1)$, one number for each (x_s, y_s) pair. Reconstruction of the fractional part of z is more difficult, but could be instrumented by a sawtooth waveform that begins at zero after each beam jump and attains the value one just before the next beam jump, T_{x0} or T_x time units later. Whether this fraction is to be added to or subtracted from an integer value of z is determined by the sign of $(z_b - z_a)$. Finally, the range, the square root of the sum of the squares of the differences, along each dimension, between final and initial coordinate values is obtained from analog square law and square root law devices.

Instrumentation Problems. Finally, on the basis of the Bell Telephone Laboratories' experiences with a flying spot store and scanner for the Morris, Illinois electronic switching system, we mention additional instrumentation problems that will be encountered (4, 5). Already discussed are scanning precision and reliability and the need for precise timing in the associated switching circuitry.

One source of error is the fluctuating signal-to-noise ratio in read-out due to electrical noise and to physical imperfections in the electron beam, phosphor screen, film storage array, and optical alignment. Significant issues of design include sensitivity, decay time, and maximum power loading per unit area of the phosphor; power requirements and deflection speeds of the cathode ray; light collection efficiency, magnification, distortion, and scattering of the optics; relative darkness of zeros and ones, spot size, scattering characteristics, and exposure requirements of the storage film; and discrimination ratio, sensitivity, and noise generation in the photocathode and photomultiplier tube.

As mentioned previously, the Bell System used a closed loop feedback comparator to obtain the desired deflection accuracy. Because their device calculates each spot location to be scanned, it is incompatible with our speed criterion. A system based on feedback control of the scanning waveform parameters may be workable, however, and further thought should be given to this possibility.

Conclusion. Our conclusion, therefore, is that the single channel flying spot store and scanner, controlled by special-purpose analog circuitry but not by the digital processor, is capable of simulating a range-only, pencil-beam sensor. The experience of the Bell System suggests the need for a major development effort. We anticipate that the most severe problem will be reliable scanning to a precision of 1,000 × 1,000 points. In the next section we present an optical multiplexing scheme which relaxes the resolution requirements and simplifies the scanning pattern.

Optically Multiplexed Flying Spot Store and Scanner

To obtain parallel read-out, the Bell Flying Spot Store focuses the phosphor's point of light through each one of a bank of optical systems, photographic films, and photomultiplier detectors, as indicated schematically in the diagram of Figure 6 (4, 5). For simplicity, only four channels are shown. Thereby one reads out simultaneously the corresponding points from each of the individual storage matrices, obtaining, in the example, four bits for every one in the nonmultiplexed case. Although there is no organization of an array of storage matrices that would make parallel read-out of direct applicability in our system, the multiplicity of channels is useful in a way which we next describe.

We assume j^2 z-layers, and place the (x, y) brute force representation of each layer on a separate film section in the storage plane. The beam, while scanning a straight line across the tube face, searches an (x, y) line for all values of z. Therefore, if a way can be found to extract the appropriate z-valued bit, the scanning pattern need only be a straight line instead of a complicated series of straight line segments interspersed with jumps. x_{r0}, y_{r0}, m_x, m_y, and T_{tot} are defined above; they characterize completely the x and y scanning waveforms, which now are ramps only.

To extract the appropriate bit of the j^2 interrogated, a switching circuit must choose and examine the corresponding photomultiplier output. Circuits identical to those described under "Calculation of the Scanning Parameters Without Use of the Digital Processor" calculate the integer part of z_b, the sign of $(z_b - z_a)$, T_{x0}, and $T_x = 1$. Switching logic then identifies the initial z-layer, thereby determining the first photomultiplier output to be gated on, followed by the direction of change of

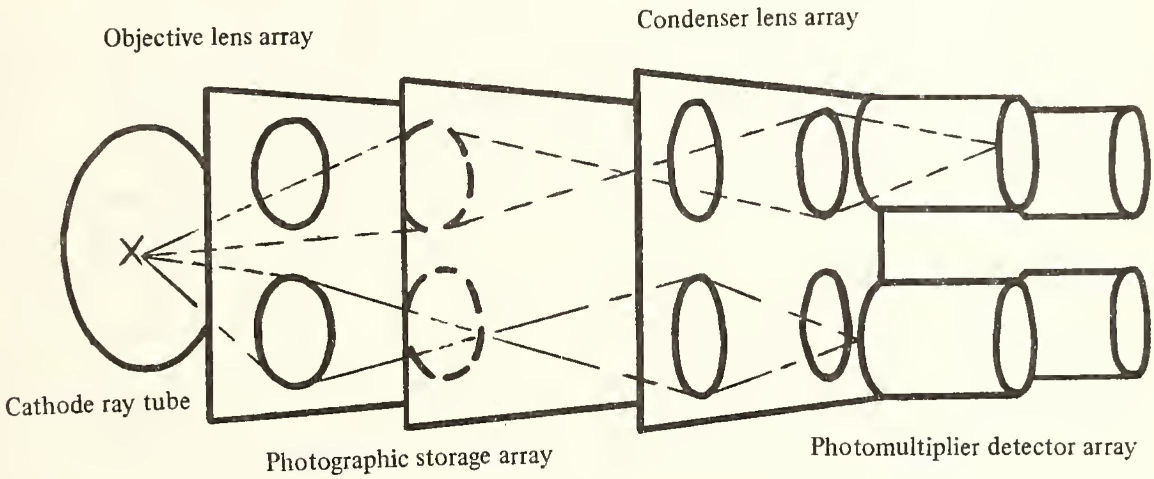


Figure 6. Optically Multiplexed Flying Spot Store and Scanner (4 Channels)

examined photomultiplier, the interval to the first change, and the interval separating all other changes. The special case of small $(z_b - z_a)$, and the cessation of the scan at the instant of an intersection or x, y, or z overflow, are handled almost identically as in the single channel scanner. Outputs of the x and y coordinates at the intersection are obtained from the x and y ramp waveforms; the z-value is calculated from the number of the "active" photomultiplier and time interpolation. The scan time is now monotonic with the horizontal projection of range, but extra componentry is required to calculate the range from the initial to final scan points. Thus the optically multiplexed system can simulate the pencil-beam, range-only detector with simpler control circuitry than the single channel system.

What advantages besides a simpler scan control has the multichannel system over the single channel one? We have estimated that in the latter case the total scanning time is upper-bounded by 1/3 msec. The scan of the multiplexed system, requiring only one sweep, could take as little as 20 to 40 μsec. Still more significant, however, is the reduction in the requisite beam positioning precision. In 6 ft of height there are 36 two-in. levels and 72 one-in. levels. Each dimension's resolution requirement is reduced by the square root of the number of horizontal layers. The reduction from 1,000 points to the order of 150 points is significant because the former is today exceedingly difficult to instrument while the latter is relatively easy. In fact, the flying spot scanner to which we now have access is accurate at the latter precision. We must temper these remarks by noting that as the number of channels is increased, the need for greater light flux from the phosphor forces an increase in spot size, and therefore an effective reduction in resolution. The Bell Laboratories report, however, that the spot diameter grows much less rapidly than the square root of the number of channels; thus the character of the result is unchanged.

The major disadvantages result from the increased cost of multiple (j^2) componentry and the optical problems of the alignment and focusing of a multichannel system. We recommend, therefore, an optically multiplexed flying spot store and scanner to reduce the beam positioning precision requirement, the scan time, and the control circuit complexity, at the price of an increase in optical and detector componentry and in optical complexity.

Potential Special-Purpose Simulation Tools

The insights provided by our study of the nature of the simulation task and some approaches toward computation systems that may carry out the task should assist one in recognizing potentially valuable new hardware if and when it is developed. As illustrations, we discuss briefly one new electron optical positioning technique, a four-access coordinate scheme under development by Philco (1), and one potential computer memory, a "corelike" storage with special-purpose access circuitry, conceived by P. L. Marcus and the author.

A particular point in the four coordinate store is accessed by specification of two variables along each dimension--the main deflection position and the main deflection angle. We assume a $k \times k$ raster divided into a matrix of $k \times k$ subrasters. Control of the main deflection position directs the beam to a particular subraster. Control of the angle determines through deflection by a focusing aperture mask the position within the subraster. The developers of the system claim that "proper design of the cathode ray device can make these two variables. . . completely independent and noninteracting" (1). The advantage of this scheme is that the required precision is now one part in k rather than one part in k.

Next we assume a brute force representation of the room environment, an $n_x \times n_y \times n_z$ array, stored in an $n_x \times n_y \times n_z$ matrix of "corelike" storage elements, corelike in the sense that the contents of a particular bit is read out by the coincidence of signals on each of the three corresponding coordinate sense wires. Reading out the contents of a set of cores in a standard digital computer, however, requires a separate read instruction addressed to each desired bit. We envision a special purpose read circuit, composed of three variable rate electronic stepping switches, each connecting read pulses to one of the sense lines along the corresponding dimension of the array. The starting connections and the stepping rates, held constant throughout one pass, are precalculated so that the bits interrogated lie along a desired straight line in the array. Thereby is simulated a pencil-beam in the room environment.

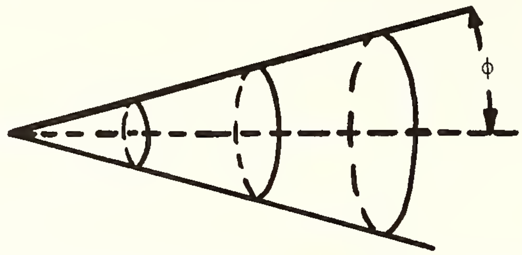
A major obstacle to implementation of such a scheme is the high cost of core storage. Yet today many new rapid access storage elements are under development, one of which may turn out to be cheap enough for use in the mobility aids simulator (7).

GENERAL-PURPOSE MOBILITY AID SIMULATOR

This chapter introduces briefly some of the issues associated with the design and operation of a general purpose mobility aid simulator. The extension of the simulation of a pencil-beam to that of a narrow- or wide-angle beam is discussed. Next we consider object identification and extraction of object descriptions, the second major task of the simulator, which is performed once the existence and location of an obstacle or interesting terrain is ascertained. We introduce the notion of a master control program and describe its chief characteristics. An important area is that of subject interaction with the simulator; the user may receive output display signals and transmit simulator control signals. Finally, a fuller discussion of the nature of the man-machine interaction is based on considerations of the types of experiments for which we plan to use the simulator.

Simulation of Beams of Finite Aperture

Of potential navigational utility to a blind man is environmental information about the existence, location, and description of objects in a sector in front of him, of which the ray is a special case with sector angle $\phi = 0°$. Unfortunately,



the only effective procedure known by us sends out a dense set of pencil-beams to sweep the sector. Recalling our earlier discussion, the reader will appreciate that an immense time is consumed by an object-centered approach that checks each surface description to see if some part of it falls within a conical sector. A brute force procedure could be more efficient than mere iteration if cubes near the dummy sensor that are intersected by more than one pencil-beam were iterrogated once rather than several times. The severe complexity of an appropriate zigzag scan that sweeps the entire sector from the dummy sensor outward, and the enormous time required to check each new point against a list of previously interrogated elements, combine to make such schemes even less efficient than pure iteration.

For the flying spot scanner pure iteration is also an obvious choice with the advantage that, especially in the multiplexed case, the time for a single scan is short enough that multiple scans may occur within the time restrictions. We seek a scanner and range finder that will generate a fan of pencil-beams without digital processing, but through the input of the parameters of the central ray and of a perturbation factor proportional to the sector angle ϕ. A special-purpose circuit must then transform the ϕ perturbation into a succession of $(x_b - x_a)$ $(y_b - y_a)$, and $(z_b - z_a)$ perturbations, holding (x_b, y_b, z_b) fixed, fixed, thereby generating a fan of pencil-beams around the central ray. The design of such a system is a major unsolved and unattempted problem. Because of the discontinuity in the z representation, separate treatment of the horizontal "fanning out" and the vertical "fanning out" could simplify the circuitry at the cost of a sector without cylindrical symmetry. This is particularly significant because of the possibility of controlled (x, y) defocusing of the cathode ray beam, thereby generating a single scan of a sector with finite aperture.

The large number of pencil-beams required by a fan of interesting aperture is disturbing. For example, if we assume a $\phi = 10°$ sector emanating from one side of a $120d \times 120d \times 36d$ room, thereby intersecting a circle of approximately $10d$ radius

on the opposite wall, then there are required on the order of 300 pencil-beams if no volume elements in the sector are to be missed. One unsatisfying solution is a fan less dense in pencil-beams that misses some elements far from the user, and therefore may miss some small obstacles.

We have sought a millisecond or quicker pencil-beam calculation to allow interpolation between successive paths determined by the dummy sensor monitor output. Another major unsolved question is whether there exist methods to interrelate this interpolation and source of more pencil-beam calculations with the source of more ray calculations due to the simulation of nonzero beam angle. Beams of finite aperture that do not fan out could be constructed from pencil beams by varying (x_b, y_b, z_b) while ($x_b - x_a$), ($y_b - y_a$), and ($z_b - z_a$) remain fixed. An investigation of the relative ease of simulation for the two types of wide beams should be undertaken. Finally, in the very common cases of intersections by many of the pencil components of a wide-angle beam, there are additional unexplored problems--the extraction of minimum range and the position coordinates from a set of multiple intersections, or, even more ambitious, the extraction of some function of the ranges of a subset of the intersections.

Object Identification and Description

How can the computer relate the existence and location of an object within a given sector to an identification and description of the object? The only general method good for every room environment is auxiliary storage of an object number (zero, if no object is present) corresponding to every three-dimensional volume element in the room. Such a system requires a million-word auxiliary store with approximately five to eight bits per word, which would probably be a disk file or drum. Because average access times are on the order of tens of milliseconds, object number extraction will lag behind the production of intersection coordinates by the scanner-range finder unless a filter selects for interrogation only a fraction of the locations listed by the scanner. The speed of object identification is no direct liability in the sense that outputs to the user need be provided only on the order of ten times a second.

This situation is, however, a potential source of error in that the intersected locations not interrogated might contain a small object in close proximity to other objects which consequently is missed. The only way to avoid such errors is separation of objects or use of an efficient filtering algorithm that transforms element coordinates into object number, or, at least, locates changes of object number in a list of volume elements. One such algorithm that works only for objects pairwise widely separated, along one or more dimensions, is object identification by the highest order bits of the element location. If such an algorithm existed, however, we could reference all objects from a list shorter than the number of elements; if it were short enough, we could include it in core storage, and eliminate the auxiliary memory unit.

We note that because successive locations to be interrogated will be relatively close together on the auxiliary store, we should obtain some reduction in the device's average access time. The order of magnitude of this effect must be investigated in terms of specific storage devices.

Finally, the coded object properties, such as "round," "flexible," "smooth," "hard," "touches the floor," "(less than) 3 feet wide," "table," and "tilted" may all be stored in core memory. They are trivially extracted, by reference from the object number, to trigger output display signals.

Master Control Program

Briefly we consider the problem of experimenter-machine interaction. In particular, how is the huge amount of data for the flying spot, auxiliary, and core storage units to be entered into memory? For this task we require a master program that controls the printing of the photographic film and the insertion of all tables into the core and auxiliary stores. The program will possess a set of object and terrain prototypes, each characterized by a small set of geometric parameters, from which a brute force representation may be constructed. Consequently the experimenter need use as input only a list of objects, each followed by a location, orientation, set of geometric parameters, and set of object descriptions. From this data the master program extracts a brute force environment representation, the object number reference list for the auxiliary store, and the description lists for core memory.

Subject-Machine Interaction

One area of subject-machine interaction is that of output signals to control the subject display. There are two related phases to the problem, the production of a display control signal by the digital processor, and the conversion of the signal by the display device into a form usable by the blind. We discuss briefly the former question only, and note that a great deal of instrumentation may be required to supply the variety of display devices with which we hope to experiment.

The simplest conceivable outputs are indications of the presence or absence of an intersection and the range to the intersection with some exploring beam. Because the pencil-beam rangefinder should operate at better than 1,000 calculations per second although the display outputs need change up to the order of ten times per second, the digital processor may obtain interesting display parameters by averaging a set of ranges, taking the minimum of a set of ranges, or measuring the rate of change of range. If a wide angle beam is constructed by a fan of pencil-beams, the density of intersections and the distribution of ranges are other possibly useful geometric parameters. Most significant, however, is the output of coded properties from the object-referenced property lists.

User control of the simulator is a second major type of machine-subject interaction. The subject may "request" output of different parameters or a change in the display rate or resolution. He may request a different angle or width of a finite aperture beam, a different number of pencil-beams, or a different relative orientation among these beams. The digital processor's program must respond immediately to a signal for a new calculation mode or display mode.

Potential Experimental Measures of Mobility

Finally, to further illuminate the nature of subject-machine interaction, we consider possible experimental measures of mobility. At the outset we note that any real-time machine processing of experimental data and results is an expendable luxury if the simulation itself should consume the entire computation capability. Besides, there are some mobility measures, such as subjective ones from the user, for which machine data processing is unnecessary.

A most interesting experimental record would be a plot, as a function of time, of subject position, subject orientation, navigation speed, and display output, superimposed spatially upon a map of the environment. A measure of subject uncertainty or hesitation, such as obtained from changes in the rate of forward movement or the "amount" of "exploration" with the dummy sensor, may help to evaluate potential mobility aids. A comparison of parameters such as speed and environmental exploration as a function of successive traversals of an environment is a measure of the assistance provided by a device in the formation of a mental picture of the environment. The collection of these three classes of data would, of course, be greatly facilitated by calculations of the digital processor. Some mobility measures related to landmark detection, such as the number of objects identified in a fixed time or the time to locate one specific object, are examples of data that may be collected efficiently without computer help.

One potentially interesting experimental mode is that of a "faked" room environment, in which the objects do not exist in the room but only in the computer representation of the environment. Such a scheme is useful to increase the apparent size of a small experimental room by rapidly changing the "contents" of the room. It is also useful to experimentally isolate the mobility aid clues from the natural environmental clues obtained by a sightless person. Such isolation, as well as an analysis of the separate roles of the natural auditory and tactile-kinesthetic clues, is of experimental interest. Finally, a faked room environment may be used in tests of the effectiveness of display devices. This approach requires increased computer participation because now only the computer is "aware" of subject "collisions" and can display them to the user and experimenter. The inverse of the number of such imaginary collisions

might be a useful experimental measure of mobility, one that the computer must tabulate.

There are, unfortunately, two severe problems to this scheme. The first is that the lack of correspondence between the true environment and the supposed environment may prove disturbing to subjects. The second problem is that of detecting collisions between the subject's body and an object. Unless we are satisfied with treating the subject as a point, the computer must track some approximation to his shape in its movement throughout the room. This would be a time-consuming and inaccurate calculation.

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Discussion

We shall make a few more general comments on the purpose, advantages, and disadvantages of the simulation facility. We stress that the computer is not intended as a potential mobility aid but only as an experimental tool to aid intelligent design of future mobility devices. Because of the risk inherent in extrapolating from experimental results in a small, somewhat artificial testing room, conclusions applicable to behavior in diverse surroundings, we have insisted upon the criterion that the testing environment be as natural as possible.

We have argued that a computer simulator is versatile, and have demonstrated the diversity of information extraction functions that it can perform. These range from answering questions about the existence and location of objects in a sector of the environment to providing descriptions of the objects. We have seen that a computer does not simulate all functions with equal ease; in particular, for the search of sectors wider than a ray we have thus far found only the inelegant solution that iterates a pencil-beam calculation. Given the object location or object number, the property look-up function is ideally suited for digital simulation, for it is accomplished by a simple indexed reference into a table. The pencil-beam calculation, while intransigent to standard digital computer approaches, is carried out efficiently by an essentially analog scan of digitally stored information. One hardware realization of this scheme is a flying spot store and scanner controlled by special purpose analog circuitry.

With these relations in mind, we suggest consideration of a version of the testing facility in which narrow- or wide-angle sensors are actually constructed in prototype form and used in conjunction with a computer simultaor of all other functions. To minimize hardware problems, we wish to take advantage of the fact that the prototype is to be used only in the experimental testing room. If we can cover every object with an energy-sensitive detector, we need construct only the energy radiating portion of a simulated "active" mobility aid. The prototype

could, for example, transmit an electromagnetic beam of a frequency to which the detector is sensitive. A signal from the surface detector of one or more of the objects provides the digital processor with a list of object surfaces in the beam path, in fact, only those "visible" to the energy source. With this information range may be calculated easily (by an object-centered digital approach, for example, or by special purpose analog circuitry), and object properties may be extracted from the tables. We recommend that the feasibility and the ramifications of such a scheme be studied.

It is important to reiterate and reinterpret one fundamental difference between the object property output signal expected from the simulator and that from real mobility devices. The simulator emits a clean, "noiseless" signal, chosen from a finite set of outputs, in which is coded the values of a set of object properties describing, for example, shape and texture. The real mobility device, however, emits a complex signal measuring some physical parameter and providing, in an information theoretic sense, information about the abstract properties of the object. It is unlikely that the simulator could be designed to emit signals of the latter character; likewise, it is unlikely that a device could extract a precise measure of such abstractions as "round," "pointed," "hard," or "rough." Thus the simulator permits tests to measure the utility of "perfect information" about certain environmental details. Such measures may prove to be upper bounds, or limiting values, on the usefulness of knowledge of a particular kind of detail as extracted, with much distortion, by all real mobility devices. The experiments should establish that many environmental details have little or no utility; they will provide valuable insights into those characteristics that are of significance to mobility.

Conclusions

After justifying the use of a rectangular coordinate system, we have considered the simulation of a pencil-beam, range-only sensor on a standard digital computer. The object-centered techniques represent objects by equations that describe their bounding surfaces; the brute force techniques approximate each object by a grid of three-dimensional elements. We have concluded that both sets of techniques fail by two orders of magnitude to achieve the goal of 1,000 pencil-beam calculations per second. We have compared and contrasted these two classes of techniques as well as the many variations within a class. Storage capacity for object-centered techniques is no problem; for brute force techniques, with reasonable occupation densities, an 8,000-word memory suffices through the use of a vertical list, array coding scheme. Calculation time for object-centered approaches varies directly as the number of surfaces, and is critically dependent upon object geometry. Calculation time for brute force approaches varies linearly with the number of grid elements

along one dimension. It may be decreased, in the simplest ray-tracing algorithm, the bullet procedure, by an increase of the bullet stepping distance at the price of a resulting loss of accuracy. For specificity, we have included a discussion of a small-scale, two-dimensional simulation on the TX-0 computer, in which a brute force array code and bullet ray tracer are used.

After presenting an interpretation of the unsuitability of a standard digital computer for the simulation of a beam's interaction with an environment, we have suggested the use of a scanner-range finder that provides data to a digital processor but is not dependent upon calculations of the processor. We have discussed in detail a single-channel and an optically multiplexed flying spot store and scanner, and presented in functional terms one realization of the requisite control circuitry. Use of the multichannel rather than the single-channel system relaxes the requirements in beam positioning precision, simplifies the control circuitry, and speeds up the scan at the price of the cost of multiple optical and detector componentry and increased optical complexity. Finally, we have presented two potential hardware developments that could be useful.

We have discussed the formation of finite aperture beams and the storage of tables of object descriptions that allow general purpose simulation. Considerations of the master control program, of the types of output display signals to be sent to the subject and simulator control signals to be provided by the subject, and of the types of experiments to be run and data processing thereby required, have sharpened our conceptions of the eventual structure and operation of the simulation system. Consequently we indicate in Figure 7 a more detailed block diagram of the proposed mobility aids simulator.

Recommendations for Future Research

We recommend the initiation of hardware design for the single-channel and multichannel flying spot store and scanner control circuitry. A careful evaluation of cost, speed, precision, reliability, and construction time are necessary to facilitate a decision between the two alternatives and to guide the development of this realization of the simulation system. We suggest an investigation of the Philco four coordinate access scheme mentioned above; its potential significance to the success of a flying spot scanner is great. Research should be undertaken on the reduction of the computer's simulation burden through the use of active energy emitters carried by the subject and energy sensitive detectors located on every object. We recommend careful attention to new hardware developments in search of instrumentation better suited to the simulation task.

Further research must be carried out on the simulation of finite aperture beams and on the interrelations of simulation, display calculations, and data analysis in the digital processor. Development of a master control program is a large task to be begun after a final decision on hardware is made. Greater

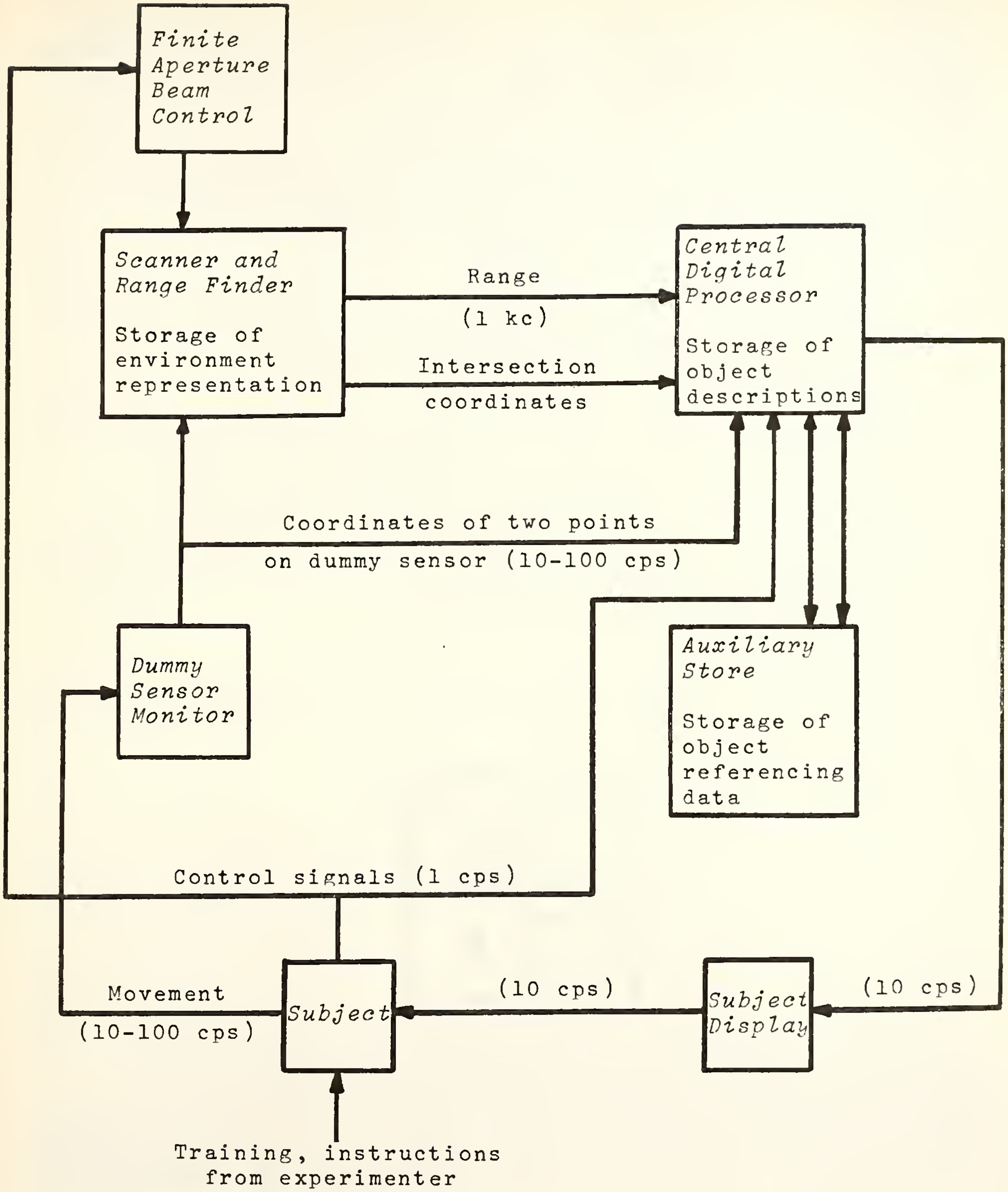


Figure 7. Block Diagram of Proposed Mobility Aids Simulation System

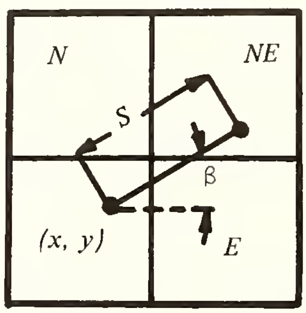
knowledge about the requirements for the auxiliary storage unit is needed. We must determine more precisely our priorities in experiments to be run, speed, generality in the room environment, and calculation accuracy in order to guide any compromises in design that must be made. This issue is immediately pressing should we wish to run preliminary experiments with a standard digital computer.

In these ways we recommend the continuation of the work reported in this paper towards the development of a computer simulation facility for mobility aids research.

Appendix 1

The Probability, per Iteration of the Two-Dimensional Bullet Procedure, of Stepping over a Corner

Let the starting point (x, y) of a step be expressed modulo d, where d equals the width of a square element, and let β be the ray's angular orientation. For simplicity, we assume $0° < \beta < 90°$; for the other three quadrants, the result is identical. We assume that the probability density function for starting point within a square element (x mod d, y mod d), is uniform over an ensemble of all exploring rays and all positions along the exploring rays. We shall initially assume a uniform distribution for the ray orientation β.

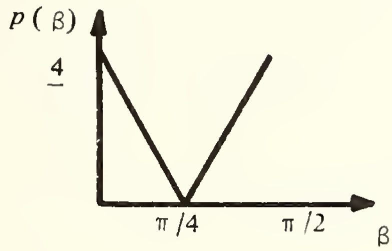


Finally, we assume that the ray cannot pass directly through a corner, and that the stepping distance $s < d$. A corner is missed if and only if the end-point of the step is in square NE, which happens if and only if $[y + s (\sin \beta)] > d$ and $[x + s (\cos \beta)] > d$. Thus the ensemble average probability, per iteration, of missing a corner is given by the expression

$$P = \int_0^{\frac{\pi}{2}} \int_{d - s(\sin\beta)}^{d} \int_{d - s(\cos\beta)}^{d} \left(\frac{dx}{d}\right) \left(\frac{dy}{d}\right) \left(\frac{d\beta}{\pi/2}\right) = \frac{s^2}{\pi d^2}$$

To upper bound this probability by 0.01, choose $(s/d) < 0.18$.

The assumption of uniformity in the (x mod d) and (y mod d) distributions is a good one. There is no reason to expect position nonuniformities at a microscopic level (measured mod d). One might expect, however, that the orientation would be more often roughly orthogonal to the walls rather than diagonally across the room. We have therefore recalculated the above probability using as the β distribution



The result, that $P = (0.8)(s^2)/(\pi d^2)$, shows a remarkable insensitivity to the details of the β distribution.

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For his inspiration and guidance, for his understanding, cordiality, and patience, and for the clever ideas which he liberally sprinkled throughout our discussions, I extend to my advisor, Professor Samuel Mason, a warm heartfelt thankyou.

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"St. Dunstan's International Conference on Sensory Devices for the Blind," H. Freiberger
"The Development of a Reading Machine for the Blind, Summary Report," G. C. Smith and H. A. Mauch
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"Annual Report, Prosthetics Research Study, July 1, 1965-June 30, 1966," E. M. Burgess
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Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Tactile display for the blind or deaf. Two variants as displayed.

Name: Recording Indicator for Tape Recorder
Source: SVCR
Bromma 3, Sweden
Availability: Preproduction prototype

Device for tactile determination of recording level.

Name: Microswitch Contact
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Contact-making device in which temperature caused by exhalation or radiation from the body surface is used for originating impulses.

Name: Voice-Operated Door Telephone
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Door telephone operated entirely by speech.

Name: "Baby-Watcher" for Parent with Impaired Hearing
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Device for detection of a child's voice, comprising microphone, amplifier, and tactile sensor.

Name: Radio-Transmission Apparatus for the Deaf
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Its purpose is to enable a deaf person anywhere, for instance in a classroom, to hear a speaker by placing the transmitter near the rostrum and holding the receiver.

Name: Telephone Amplifier
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Small portable amplifier for application to telephone receivers; for use by persons with defective hearing.

Name: Communication Apparatus for the Deaf-Blind
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Radio-transmission of different signals to the deaf-blind in tactile form.

Name: Electric Braille Typewriter
Source: SVCR
Bromma 3, Sweden
Availability: Preproduction prototype

Accessory to ordinary braille typewriter to compensate insufficient force of impact.

Name: Marker for End Position on Braille Typewriter with Tactile Sensor for Use by Deaf-Blind
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Name: Writing Aid for the Visually Handicapped
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Draft board with ruler and set square marked with braille signs, together with special ratchet in holder, to make impressions legible from the top surface.

Name: Guiding Thread for the Blind
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Magnetic thread, laid down at traffic crossings, alongside pavements, railway platforms, etc. Magnetic field is picked up by a vibrator built into the ferrule of a stick, through which it is communicated to a tactile transmitter at the handle.

Name: Electronic Thermometer for the Visually Handicapped
Source: SVCR
Bromma 3, Sweden
Availability: Preproduction prototype

A thermistor is the temperature-sensitive device; and an audible output is counterbalanced to zero by a potentiometer at the correct temperature. Tactile display by identification of position of potentiometer.

Name: Apparatus for Recording Measurements in Speech Form
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Apparatus for conversion of recorded measurements into audible form, to enable the visually handicapped to perform certain kinds of work.

Name: Football for the Visually Handicapped
Source: SVCR
Bromma 3, Sweden
Availability: Preproduction prototype

Football with acoustic signal for use by blind or partially blind.

Name: Buccal Contact-Making Device
Source: SVCR
Bromma 3, Sweden
Availability: From supplier

A device for contact-making by biting, consisting of two contact plates fitted into a plastic cover: contact made by compression through biting.

Name: Device for Contact-Making by Blowing
Source: SVCR
Bromma 3, Sweden
Availability: From supplier

Contact-maker consisting of a microswitch equipped with flaps, blowing upon which creates the electric circuit.

Name: Pressure Contact Device
Source: SVCR
Bromma 3, Sweden
Availability: From supplier

Contact-maker consisting of a microswitch mounted between two plates; electric circuit made by compression.

Name: Alarm Clock for the Hard-of-Hearing
Source: SVCR
Bromma 3, Sweden
Availability: From supplier

Vibrator with electric clock, to be placed under pillow.

Name: Doorbell with Tactile Receiving Device for the Deaf-Blind
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Name: Inhalation and Exhalation Contact
Source: SVCR
Bromma 3, Sweden
Availability: From supplier

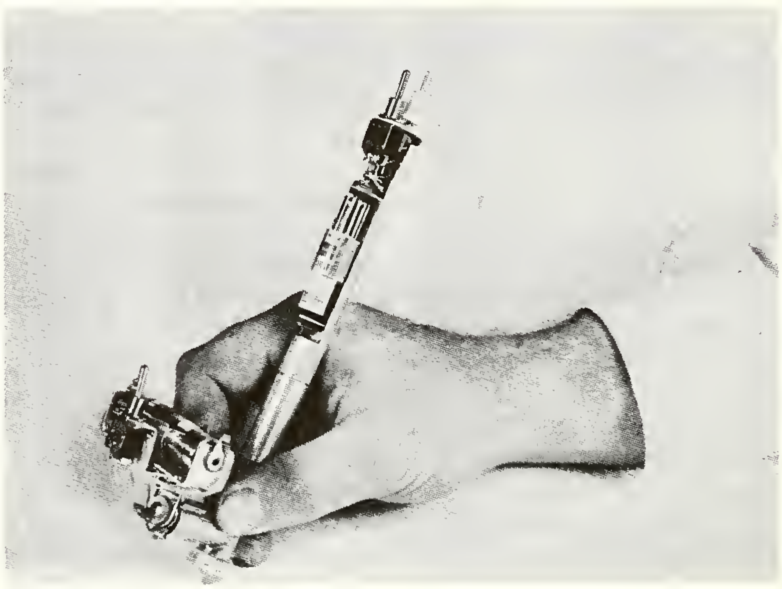
System to enable handicapped to operate electrical devices such as radio, TV, etc. Simplified variant of the British "Possum."

Name: Communication Apparatus for the Deaf-Blind
Source: SVCR
Bromma 3, Sweden
Availability: Laboratory prototype

Radio-transmission of signals to the deaf-blind in tactile form.

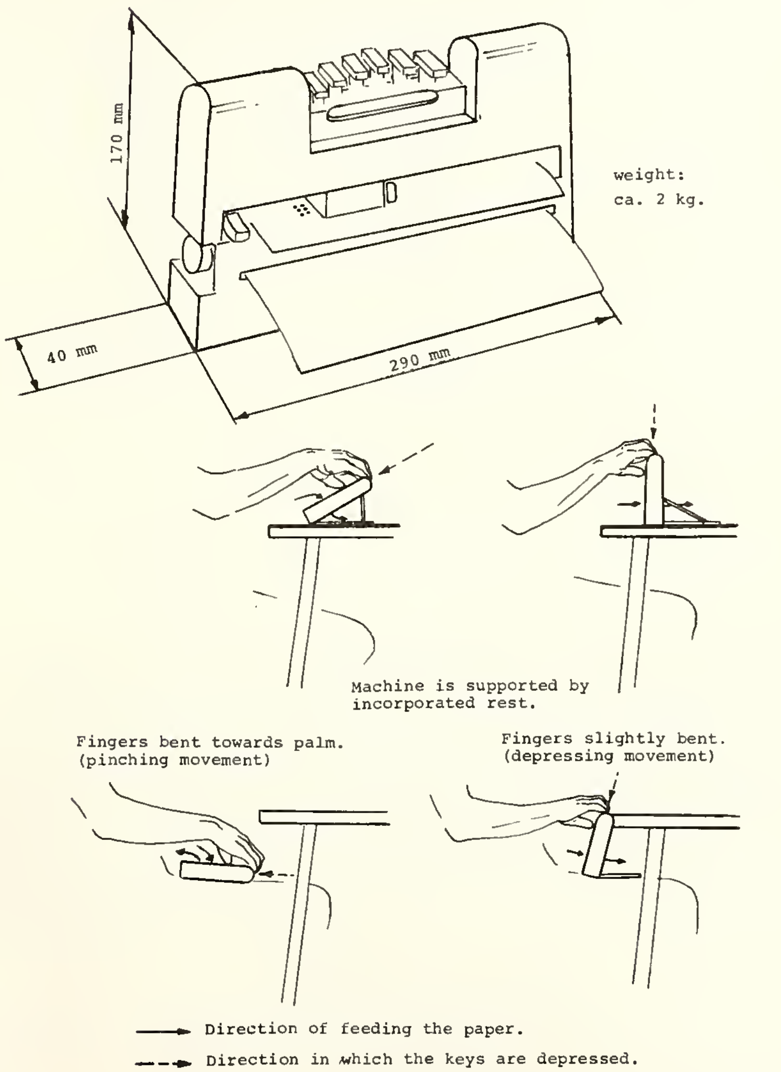
Name: Compass for the Blind
Source: SVCR
Bromma 3, Sweden
Availability: Production prototype

Name: Light-Sensitive Photocell
Source: Dr. Thomas R. Carver
Palmer Physical Laboratory
Princeton University
Princeton, New Jersey 08540
Availability: Experimental prototype



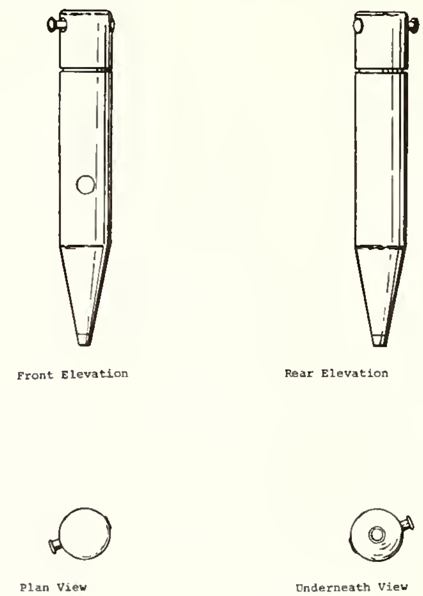
Photocell converts light intensities into equivalent electrical analogs; output display is via an integral loudspeaker. Device was constructed for a blind student's use, and several variants of the system are available in drawings and specifications.

Name: Portable Brailler
Source: Ch. J. Snijders
Technische Hogeschool te Eindhoven
Insulindelaan 2
Eindhoven, The Netherlands
Availability: Experimental prototype



This device is small, light, inconspicuous, and quiet in operation. It takes sheets of standard braille paper, or rolls, up to 25 cm in width, fed in one side and issuing out the other; paper can be torn off at any time. Line length is 30 characters. The touch is light. The keys are arranged in a fanlike array, so that one-handed operation is possible. End-of-line is signaled by a tap instead of bell. Embossing is readable immediately it is made.

Name: Recording Level Indicator
Source: Mr. Murray Ward
Hartley
Green Lane
Milford, Godalming
Surrey, England
Availability: Experimental prototype



This circuit was designed primarily to give audible indication to a blind person of the recording level on a tape recorder. When the recording level is set too high, an audio tone is given out. Other possible applications are as an aid to the amateur movie enthusiast during the recording of sound on film, or a simple industrial level-warning device.

Name: Keith Projector for Raised Line Drawing
Source: Efco Associates
5 Valley View Road
Warren Turnpike
Plainfield, New Jersey
Availability: From supplier
Price: $125 per set

The projector eliminates pantograph and other methods in copying and enlarging drawings for transcribing from the printed book to raised line form. The book is placed on top of the device; a mirror image of the drawing then appears on a platform below. The platform includes a surgical rubber mat. A 1/2-mil aluminum white vinyl coated sheet is locked into a preset frame over the mat. The mirror image of the drawing, projected on the white surface, is gone over with a toothed wheel embossing tool, and a finished metal master is produced. Masters are thermoformed for Braillon copies.

Name: Directional Arrow Embossing Tool
Source: Recordings for the Blind, Inc.
215 East 58th Street
New York, N.Y. 10022
Availability: From supplier

The trace of the toothed wheel feels smooth when followed in one direction, but presents obstacles and gives a very coarse feeling in the opposite direction. This is but one of a series of tools developed under a research program to develop better embossing aids.

Name: Braille Dot Inverter
Source: Mr. James C. Swail
Radio and Electrical Engineering Division
National Research Council
Ottawa 2, Canada
Availability: Science for the Blind, Inc., Haverford, Pa.

This device raises dots on the upward or working side of a braille page, doing away with the necessity of reversing the work. It is intended mainly for mapmaking and classroom mathematical work.

Name: Folding Cane
Source: Mr. James C. Swail
Radio and Electrical Engineering Division
National Research Council
Ottawa 2, Canada
Availability: Experimental prototype

The cane is made in several sections of half-inch diameter Dural tubing, with precision-ground stainless steel cones and sockets fitted into their ends. Small holes in the center of the cones permit running a nylon cable the full length of the cane, attached firmly at the lower end, and exerting a three-pound tension via a clock type spring in the handle. The handle also serves as a clip to retain the sections in a flat pack measuring 11 in. x 3-1/2 in. and weighing 11 oz.

Name: Optical Probe
Source: Mr. James C. Swail
Radio and Electrical Engineering Division
National Research Council
Ottawa 2, Canada
Availability: Experimental prototype

Name: Braille Sliderule
Source: Mr. James C. Swail
Radio and Electrical Engineering Division
National Research Council
Ottawa 2, Canada
Availability: Experimental prototype

Name: Carpenter's or Machinist's Level
Source: Mr. James C. Swail
Radio and Electrical Engineering Division
National Research Council
Availability: Ottawa 2, Canada
Availability: Experimental prototype

An electronic device, this level emits a tone which disappears when the instrument is exactly level. The precision is approximately two min of arc or one thirtieth of a degree.

Name: Optical Probe
Source: Royal National Institute for the Blind
224 Great Portland Street
London W.1, England
Availability: Production prototype

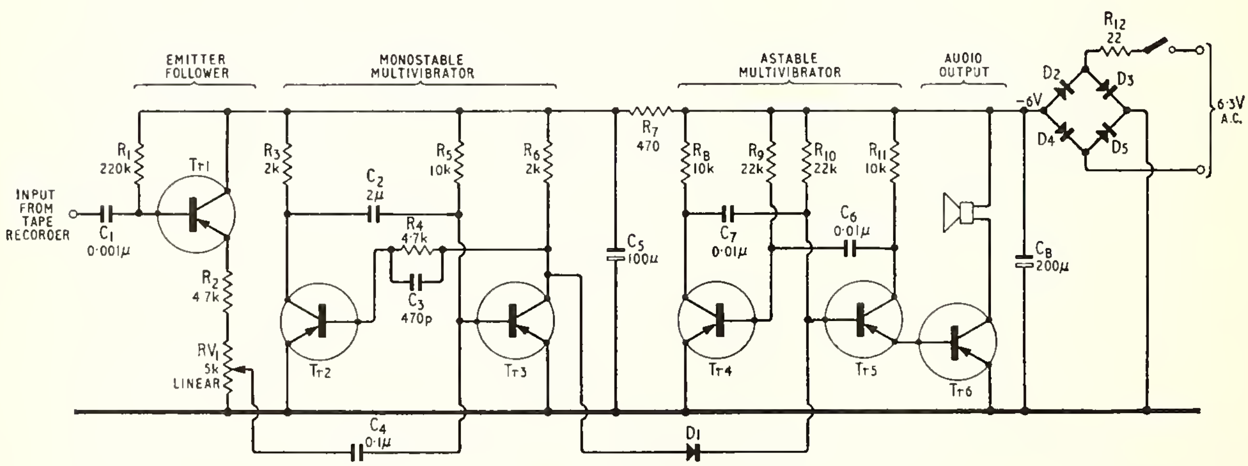


Fig. 1. Circuit diagram of the recording level indicator.

A general purpose, pocket-sized instrument to detect and convert light directly into sound. The frequency of the sound rises proportionally with intensity of light (no signal in darkness, shrill whistle under maximum illumination).

Name: Recognition Type Reading Machine
Source: School of Applied Physics
University of Bradford
Bradford, England
Availability: Laboratory prototype

Name: Binaural Spectacles Mobility Aid
Source: Lansing Community College
Lansing, Michigan
Availability: Experimental prototype

Name: Science for the Blind Meter Reader
Source: Science for the Blind, Inc.
221 Rock Hill Road
Bala Cynwyd, Pa. 19004
Availability: From supplier
Price: $40.00

The Science for the Blind meter reader consists of a small metal box with sloping panel, on which is located a braille scale with knob and pointer. The meter reader may be connected across the terminals of any visual meter movement to allow readings to be taken by correlating an auditory signal with the braille scale.

The sensitivity of the reader is approximately 150 mv full scale; it works on dc instruments only, but may be adapted for use with ac instruments by using a diode/capacitor rectifier unit and a voltage divider that has a known ratio and produces less than 150 mv across the meter reader. The instrument is intended primarily for connection to the meter movement of other measuring instruments.

Name: Lathe Duplicator Attachment
Source: Nicholas Lalli
113 N. Portland Avenue
Ventnor, New Jersey
Availability: From supplier.

This recently patented device (No. 3,277,933) was invented by a skilled cabinet maker for use by blind persons. Further descriptive material available upon request.